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Physics-Based Infrared Terrain Radiance Texture Model

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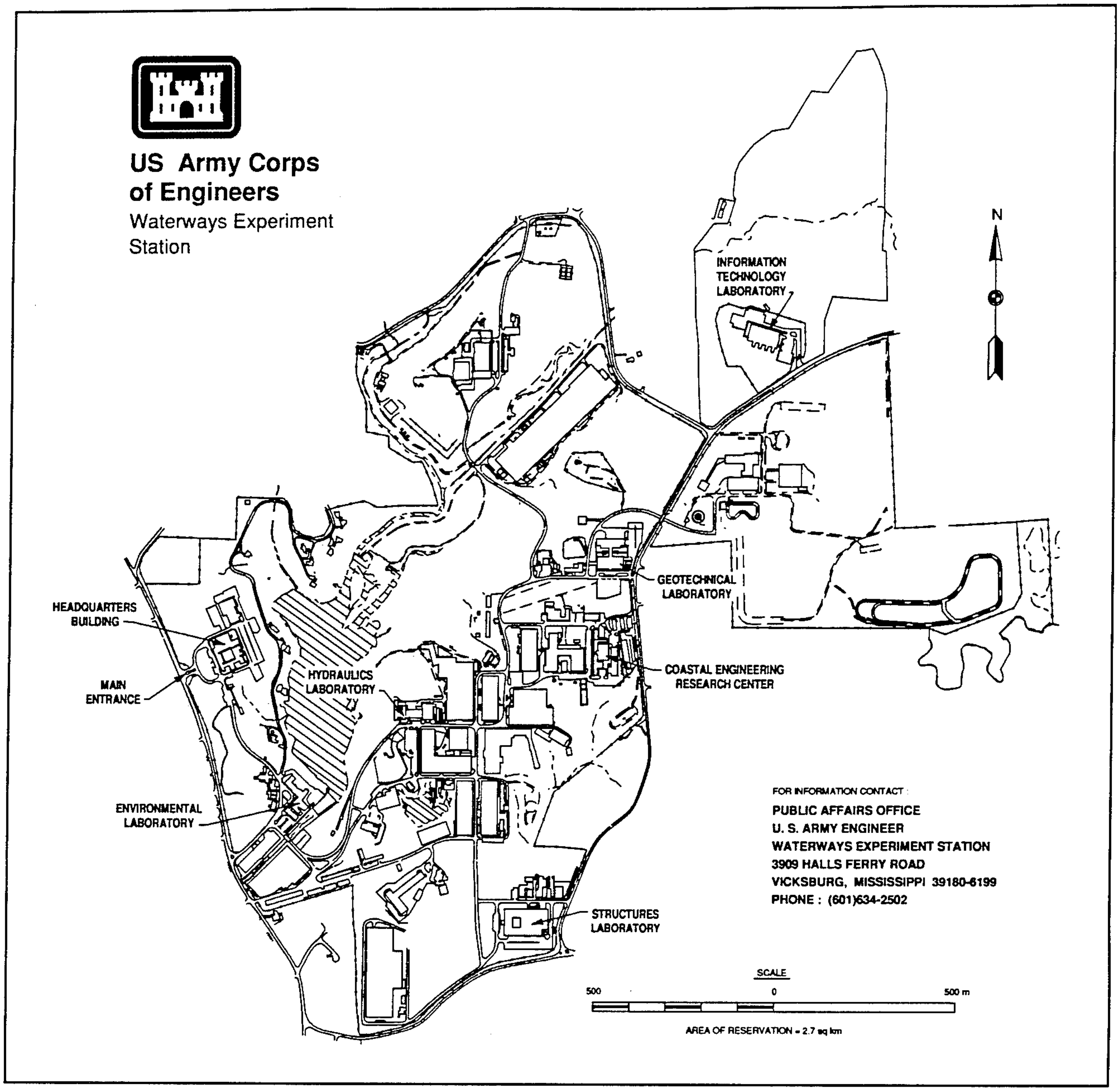

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2 Physical Parameter Metrics for Terrain

A terrain physical parameter metric is a set of constants that relates the radiance statistics of an IR image to the physical parameters that describe the terrain. Two physical parameter metrics are required for each terrain feature because both the standard deviation and correlation length of the radiance must be related to the physical parameters of the terrain surface.

Bare Soil Surface

The physical parameters necessary to describe the average and statistical properties of terrain radiance are:

ε_s = long wave emissivity of soil

a_s = short wave absorptivity of soil

k_s = heat conductivity of soil

μ_s = thermal diffusivity of soil

γ_s = soil moisture

m_s = average terrain slope of soil terrain

These parameters can be written as a physical parameter row matrix for soil terrain areas

$$P_s = (1 \ \varepsilon_s \ a_s \ k_s \ \mu_s \ \gamma_s \ m_s) \tag{1}$$

where the unity symbol is added for mathematical convenience. These are the minimum number of physical parameters that are required to determine terrain radiance.

Associated with the row matrix of physical parameters are two additional row matrices that are required for the calculation of terrain radiance texture. These are the physical parameter metric matrices, one associated with the standard deviation of terrain radiance and the other associated with the correlation length of the terrain radiance. The physical parameter metric associated with the standard deviation of the soil terrain radiance is as follows:

$$b_s = (b_0\ b_1\ b_2\ b_3\ b_4\ b_5\ b_6) \tag{2}$$

where the b's are empirical constants that characterize the standard deviation of the radiance for soil terrain. The physical parameter metric associated with the correlation length of the radiance of soil terrain is as follows:

$$c_s = (c_0\ c_1\ c_2\ c_3\ c_4\ c_5\ c_6) \tag{3}$$

where the c's are a set of seven empirical constants that characterize the correlation length of the radiance of the bare soil surface.

Grass and Short Vegetation

For a vegetated surface such as grass or secondary vegetation such as bushes, the main physical parameters that are necessary for the radiance calculation are:

ε_{lv} = long wave emissivity of green vegetation

a_{lv} = short wave absorptivity for green vegetation

m_{lv} = average terrain slope for green vegetation

ε_{dv} = long wave emissivity of brown vegetation

a_{dv} = short wave absorptivity for brown vegetation

m_{dv} = average terrain slope for brown vegetation

A reasonable approximation might be $m_s = m_{lv} = m_{dv}$. The physical parameters for vegetation can be written as two row matrices of the form:

$$P_{lv} = (1\ \varepsilon_{lv}\ a_{lv}\ m_{lv}) \tag{4}$$

$$P_{dv} = (1\ \varepsilon_{dv}\ a_{dv}\ m_{dv}) \quad (5)$$

Corresponding to these vegetation parameters are the physical parameter texture metrics that are associated with the standard deviation and the correlation length of the radiance texture of the green and brown vegetation components. Thus the physical parameter metrics associated with the standard deviation of the radiance of the green and brown vegetation are:

$$e_{1v} = (e_0\ e_1\ e_2\ e_3) \quad (6)$$

$$f_{dv} = (f_0\ f_1\ f_2\ f_3) \quad (7)$$

where the e's and f's are empirical constants that describe the standard deviation of the vegetation radiance. The physical parameter metrics for the correlation length of the radiance of green and brown vegetation are:

$$g_{1v} = (g_0\ g_1\ g_2\ g_3) \quad (8)$$

$$h_{dv} = (h_0\ h_1\ h_2\ h_3) \quad (9)$$

and where the g's and the h's are constants that describe the correlation length of the radiance signature of the vegetation.

Forest Canopies

For forested canopies, the basic physical parameters that are necessary for the radiance statistics calculations are:

ε_f = long wave emissivity of leaves

α_f = long wave absorptivity of leaves

ε_s = long wave emissivity of soil

α_s = long wave absorptivity of soil

a_f = short wave absorptivity of leaves

l_f = leaf area index

l_s = leaf slope distribution

r_f = stomatal resistance to water vapor diffusion

where heat storage has been ignored. These physical parameters for forest canopies are represented by the following row matrix:

$$P_f = (1 \ \varepsilon_f \ \alpha_f \ \varepsilon_s \ \alpha_s \ a_f \ l_f \ l_s \ r_f) \tag{10}$$

The corresponding physical parameter texture metric that describes the standard deviation of the forest canopy radiance is described by

$$p_f = (p_0 \ p_1 \ p_2 \ p_3 \ p_4 \ p_5 \ p_6 \ p_7 \ p_8) \tag{11}$$

while the texture metric that describes the correlation length of the radiance of forest canopies is given by:

$$q_f = (q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8) \tag{12}$$

where the p's and the q's are empirical constants.

The physical parameter metrics that are introduced in this section will now be used to develop a physics-based radiance texture model.

3 Physics-Based IR Terrain Radiance Texture Model

The physics-based radiance texture model is loosely based on the numerical conclusions of some previous work in this area (Ben-Yosef et al. 1985, 1987; Ben Yosef, Wilner, and Abitbol 1986). These conclusions are that (a) the standard deviation of the terrain radiance is proportional to the solar loading, and (b) the correlation length is inversely proportional to the solar loading. These conclusions need to be altered as can be seen from the extreme case where the emissivity of terrain surface is taken to have a zero value, because in this case the thermal emission is zero irrespective of the solar loading. A little thought suggests that the more appropriate statements should be (c) the standard deviation of the terrain radiance is related to the average terrain radiance, and (d) the correlation length of the terrain radiance is inversely related to the average terrain radiance. This is a more reasonable relationship because now if the terrain emissivity has a zero value, the mean radiance has a zero value, the standard deviation of the radiance has a zero value, and the correlation length is infinite.

Terrain Radiance Texture Model for Bare Soils

In this report, the standard deviation and correlation length of the radiance for bare soil areas are described using the following matrix equations

$$\sigma_{Ns} = r^{\eta} N_s^{\delta} b_s \tilde{P}_s \tag{13}$$

$$\rho_{Ns} = r^{\kappa} N_s^{\beta} c_s \tilde{P}_s \tag{14}$$

where

σ_{Ns} = standard deviation of soil terrain radiance

r = resolution, pixel/m

N_s = average radiance of bare soil in a specified wave band, $Wm^{-2}\ sr^{-1}$

b_s = empirical physical parameter metric for the standard deviation of bare soil radiance as represented by Equation 2

$\widetilde{P}_s$ = transpose column physical parameter matrix for bare soil that is obtained from Equation 1

ρ_{Ns} = correlation length of soil radiance, m

c_s = empirical physical parameter metric for the correlation length of soil radiance as represented in Equation 3

δ = empirical exponent

β = empirical exponent

η = empirical exponent

κ = empirical exponent

Equations 13 and 14 can be rewritten as:

$$\sigma_{Ns} = r^{\eta} N_s^{\delta} M_{\sigma s} \tag{15}$$

$$\rho_{Ns} = r^{\kappa} N_s^{\beta} M_{\rho s} \tag{16}$$

where

$$M_{\sigma s} = b_0 + b_1 \varepsilon_s + b_2 a_s + b_3 k_s + b_4 \mu_s + b_5 \gamma_s + b_6 m_s \tag{17}$$

$$M_{\rho s} = c_0 + c_1 \varepsilon_s + c_2 a_s + c_3 k_s + c_4 \mu_s + c_5 \gamma_s + c_6 m_s \tag{18}$$

The soil terrain radiance is given by:

$$N_s = \varepsilon_s \int_{\nu_1}^{\nu_2} N_\nu^s \, d\nu \tag{19}$$

where $N_\nu^s = N_\nu^s(\nu,T_s)$ = Planck function for bare soil, and T_s = bare soil temperature as predicted by the WESTHERM. Thus in general:

$$T_s = T_s(\varepsilon_s,a_s,k_s,\mu_s,\gamma_s,m_s,\ \text{weather, time, season}) \tag{20}$$

$$N_s = N_s(\varepsilon_s,a_s,k_s,\mu_s,\gamma_s,m_s,\Delta\nu,\ \text{weather, time, season}) \tag{21}$$

where $\Delta\nu = \nu_2 - \nu_1$ = wave band. Both T_s and N_s are predicted by the WESTHERM. Equations 15-18 show that, in general, 16 constants are required for the semitheoretical description of the radiance texture for a soil terrain area.

A simplification of Equations 15-19 can be obtained by considering only zeroth order terms which gives:

$$M_{\sigma s}^{o} = b_o \tag{22}$$

$$M_{\rho s}^{o} = c_o \tag{23}$$

Then Equations 15 and 16 become:

$$\sigma_{Ns}^{o} = b_o r^{\eta} N_s^{\delta} \tag{24}$$

$$\rho_{Ns}^{o} = c_o r^{\kappa} N_s^{\beta} \tag{25}$$

where the empirical exponents δ, β, η, and κ are given in Items 14 through 16 of Appendix A. Within this approximation, only two constants, b_o and c_o, need to be determined empirically for a semiempirical texture model for soil terrain radiance.

Terrain Radiance Texture Model for Grass and Short Vegetation

Consider now the case of grass or short vegetation with a partial cover over soil. The standard deviation and correlation length of the radiance of grass or short vegetation covering soil is given by:

$$\sigma_{Nvs} = \left\{(1 - x_v)\,\sigma^2_{Ns} + x_v\left[(1 - x_{lv})\,\sigma^2_{Ndv} + x_{lv}\,\sigma^2_{Nlv}\right]\right\}^{1/2}$$

$$= r^{\eta}\left\{(1 - x_v)\,M^2_{\sigma s}\,N_s^{2\delta} + x_v \left[(1 - x_{lv})\,M^2_{\sigma dv}\,N_{dv}^{2\delta} + x_{lv}\,M^2_{\sigma lv}\,N_{lv}^{2\delta}\right]\right\}^{1/2} \tag{26}$$

$$\rho^{-1}_{Nvs} = \ln\left\{(1 - x_v)\exp(-1/\rho_{Ns}) + x_v\left[(1 - x_{lv})\exp(-1/\rho_{Ndv}) + x_{lv}\exp(-1/\rho_{Nlv})\right]\right\} \tag{27}$$

where σ_{Ns} and ρ_{Ns} are given by Equations 24 and 25, and where

$$\sigma_{Ndv} = r^{\eta}N^{\delta}_{dv}\,f_{dv}\,\tilde{P}_{dv} = r^{\eta}M_{\sigma dv}\,N^{\delta}_{dv} \tag{28}$$

$$\sigma_{Nlv} = r^{\eta}N^{\delta}_{lv}\,e_{lv}\,\tilde{P}_{lv} = r^{\eta}M_{\sigma lv}\,N^{\delta}_{lv} \tag{29}$$

$$\rho_{Ndv} = r^{\kappa}N^{\beta}_{dv}\,h_{dv}\,\tilde{P}_{dv} = r^{\kappa}M_{\rho dv}\,N^{\beta}_{dv} \tag{30}$$

$$\rho_{Nlv} = r^{\kappa}N^{\beta}_{lv}\,g_{lv}\,\tilde{P}_{lv} = r^{\kappa}M_{\rho lv}\,N^{\beta}_{lv} \tag{31}$$

where the empirical exponents δ, β, η, and κ are given in Items 14 through 16 of Appendix A

where

σ_{Nvs} = standard deviation of radiance of vegetation and soil terrain, $Wm^{-2}\ sr^{-1}$

σ_{Ndv} = standard deviation of radiance for brown vegetation, $Wm^{-2}\ sr^{-1}$

σ_{Nlv} = standard deviation of radiance for green vegetation, $Wm^{-2}\ sr^{-1}$

ρ_{Nvs} = correlation length of radiance of vegetation and soil terrain, m

ρ_{Ndv} = correlation length of radiance for brown vegetation, m

ρ_{Nlv} = correlation length of radiance for green vegetation, m

x_v = fraction of terrain that is covered by vegetation

x_{lv} = fraction of vegetation cover that is green

N_{dv} = average radiance for brown vegetation in a specified wave band, $Wm^{-2}\ sr^{-1}$

f_{dv} = physical terrain metric for standard deviation of radiance from dead vegetation as represented by Equation 7

$\widetilde{P}_{dv}$ = transpose column physical parameter matrix for brown vegetation that is obtained from Equation 5

N_{lv} = average radiance for green vegetation in a specified wave band, $Wm^{-2}\ sr^{-1}$

e_{lv} = physical terrain metric for standard deviation of radiance from green vegetation as represented by Equation 6

$\widetilde{P}_{lv}$ = transpose column physical parameter matrix for green vegetation that is obtained from Equation 4

h_{dv} = physical terrain metric for the correlation length of the radiance from brown vegetation as represented in Equation 9

g_{lv} = physical terrain metric for the correlation length of the radiance of green vegetation as represented by Equation 8

where $M_{\delta s}$ and $M_{\rho s}$ are given by Equations 17 and 18, respectively, and where:

$$M_{\sigma dv} = f_o + f_1\varepsilon_{dv} + f_2 a_{dv} + f_3 m_{dv} \tag{32}$$

$$M_{\sigma lv} = e_o + e_1\varepsilon_{lv} + e_2 a_{lv} + e_3 m_{lv} \tag{33}$$

$$M_{\rho dv} = h_o + h_1\varepsilon_{dv} + h_2 a_{dv} + h_3 m_{dv} \tag{34}$$

$$M_{\rho lv} = g_o + g_1\varepsilon_{lv} + g_2 a_{lv} + g_3 m_{lv} \tag{35}$$

The average soil radiance N_s is given by Equation 19 and where the average radiance for brown and green vegetation is given by:

$$N_{dv} = \varepsilon_{dv} \int_{\nu_1}^{\nu_2} N_\nu^{dv} \, d\nu \tag{36}$$

$$N_{lv} = \varepsilon_{lv} \int_{\nu_1}^{\nu_2} N_\nu^{lv} \, d\nu \tag{37}$$

where

$N_\nu^{dv} = N_\nu^{dv} (\nu, T_{dv})$ = Planck function for brown vegetation

$N_\nu^{lv} = N_\nu^{lv} (\nu, T_{lv})$ = Planck function for green vegetation

and T_{dv} and T_{lv} = temperature of brown and green vegetation, respectively.

Therefore:

$N_{dv} = N_{dv} (\varepsilon_{dv}, a_{dv}, m_{dv}, \Delta\nu$, weather, time, season)

$N_{lv} = N_{lv} (\varepsilon_{lv}, a_{lv}, m_{lv}, \Delta\nu$, weather, time, season)

$T_{dv} = T_{dv} (\varepsilon_{dv}, a_{dv}, m_{dv}$, weather, time, season)

$T_{lv} = T_{lv} (\varepsilon_{lv}, a_{lv}, m_{lv}$, weather, time, season)

where $\Delta\nu = \nu_2 - \nu_1$ = wave band. The WESTHERM computer program calculates T_{dv}, T_{lv}, N_{dv}, and N_{lv}. Equations 26-35 show that 16 constants are required to predict the radiance texture of grass and short vegetation.

If no bare soil spots are visible and the vegetation cover is complete, then $x_v = 1$ and Equations 26 and 27 become:

$$\begin{aligned} \sigma_{Nv} &= \left[(1 - x_{lv})\, \sigma^2_{Ndv} + x_{lv}\, \sigma^2_{Nlv}\right]^{1/2} \\ &= r^{\eta}\left[(1 - x_{lv})\, M^2_{\sigma dv}\, N^{2\delta}_{dv} + x_{lv}\, M^2_{\sigma lv}\, N^{2\delta}_{lv}\right]^{1/2} \end{aligned} \tag{38}$$

$$\rho^{-1}_{Nv} = -\ln\left[(1 - x_{lv}) \exp(-1/\rho_{Ndv}) + x_{lv} \exp(-1/\rho_{Nlv})\right] \tag{39}$$

If seasonal effects are neglected and all vegetation is considered alive in the vegetation cover, then $x_{lv} = 1$ and Equations 26 and 27 become in general

$$\begin{aligned} \sigma_{Nlvs} &= \left[(1 - x_v)\, \sigma^2_{Ns} + x_v\, \sigma^2_{Nlv}\right]^{1/2} \\ &= r^{\eta}\left[(1 - x_v)\, M^2_{\sigma s}\, N^{2\delta}_{s} + x_v\, M^2_{\sigma lv}\, N^{2\delta}_{lv}\right]^{1/2} \end{aligned} \tag{40}$$

$$\rho^{-1}_{Nlvs} = -\ln\left[(1 - x_v) \exp(-1/\rho_{Ns}) + x_v \exp(-1/\rho_{Nlv})\right] \tag{41}$$

If seasonal effects are neglected for the case of a complete vegetation cover, then $x_v = 1$ and $x_{lv} = 1$ and Equations 38 and 39 give:

$$\sigma_{Nv} = \sigma_{Nlv} = r^{\eta} N^{\delta}_{lv}\, M_{\sigma lv} \tag{42}$$

$$\rho_{Nv} = \rho_{Nlv} = r^{\kappa} N^{\beta}_{lv}\, M_{\rho lv} \tag{43}$$

A simplification occurs in Equations 26-43 by neglecting higher order terms and considering only the zeroth order terms in Equations 32-35 with the result that:

$$M^{o}_{\sigma dv} = f_o \tag{44}$$

$$M^{o}_{\sigma lv} = e_o \tag{45}$$

$$M^{o}_{\rho dv} = h_o \tag{46}$$

$$M^{o}_{\rho lv} = g_o \tag{47}$$

Within this approximation, only four constants are required to describe the radiance statistics of vegetation. Combining Equations 22, 23, 26, 27 and 44-47 gives:

$$\sigma^{o}_{Nvs} = r^{\eta} \left\{(1 - x_v)\, b_o^2\, N_s^{2\delta} + x_v \left[(1 - x_{lv})\, f_o^2\, N_{dv}^{2\delta} + x_{lv}\, e_o^2\, N_{lv}^{2\delta}\right]\right\}^{1/2} \tag{48}$$

and ρ^{o}_{Nvs} is calculated from Equation 27 by using Equation 25 and

$$\rho^{o}_{Ndv} = h_o r^{\kappa} N_{dv}^{\beta} \tag{49}$$

$$\rho^{o}_{Nlv} = g_o r^{\kappa} N_{lv}^{\beta} \tag{50}$$

with the result that

$$(\rho^{o}_{Nvs})^{-1} = -\ln \left\{(1 - x_v) \exp(-1/\rho^{o}_{Ns}) + x_v \left[(1 - x_{lv}) \exp(-1/\rho^{o}_{Ndv}) + x_{lv} \exp(-1/\rho^{o}_{Nlv})\right]\right\} \tag{51}$$

which are valid for combined vegetation and soil terrain. Equations 48-51 show that within the zeroth order approximation, only six constants, b_o, c_o, e_o, f_o, g_o, and h_o, are required to be determined empirically for a semitheoretical description of the radiance texture for a vegetated soil terrain surface.

Terrain Radiance Texture Model for Forest Canopies

The standard deviation and correlation length of the radiance of forest canopies is described by:

$$\sigma_{Nf} = r^{\eta} N_f^{\delta}\, p_f\, \tilde{P}_f \tag{52}$$

$$\rho_{Nf} = r^{\kappa} N_f^{\beta}\, q_f\, \tilde{P}_f \tag{53}$$

where the empirical exponents δ, β, η, and κ for forest canopies were not determined in this study, and where

σ_{Nf} = standard deviation of forest canopy radiance

N_f = average radiance of forest canopy in a specified wave band, $Wm^{-2}\ sr^{-1}$

p_f = empirical physical parameter metric for the standard deviation of forest canopy radiance as represented by Equation 11

$\tilde{P}_f$ = transpose column physical parameter matrix for forest canopies that is obtained from Equation 10

ρ_{Nf} = correlation length of forest canopy radiance, m

q_f = empirical physical parameter metric for the correlation length of forest canopy radiance as represented by Equation 12

Equations 52 and 53 can be rewritten as:

$$\sigma_{Nf} = r^{\eta} N_f^{\delta}\, M_{\sigma f} \tag{54}$$

$$\rho_{Nf} = r^{\kappa} N_f^{\beta} M_{\rho f} \tag{55}$$

where

$$M_{\sigma f} = p_0 + p_1\varepsilon_f + p_2\alpha_f + p_3\varepsilon_s + p_4\alpha_s + p_5 a_f + p_6 l_f + p_7 l_s + p_8 r_f \tag{56}$$

$$M_{\rho f} = q_0 + q_1\varepsilon_f + q_2\alpha_f + q_3\varepsilon_s + q_4\alpha_s + q_5 a_f + q_6 l_f + q_7 l_s + q_8 r_f \tag{57}$$

The average forest canopy radiance is given by:

$$N_f = \varepsilon_f \int_{\nu_1}^{\nu_2} N_\nu^f \, d\nu \tag{58}$$

where

$N_\nu^f = N_\nu^f(\nu, T_f)$ = Planck function for forest canopy

and where T_f = forest canopy surface temperature as predicted by WESTHERM. Therefore, in general:

$$T_f = T_f(\varepsilon_f, a_f, l_f, G_f, m_f, \text{weather, time}) \tag{59}$$

$$N_f = N_f(\varepsilon_f, a_f, l_f, G_f, m_f, \Delta\nu, \text{weather, time}) \tag{60}$$

where $\Delta\nu = \nu_2 - \nu_1$ = wave band. Both T_f and N_f are calculated by the WESTHERM. Equations 52-57 show that for the general case, 20 empirical constants are required for a semiempirical description of the radiance texture of forest canopies.

Equations 52-57 can be simplified by dropping all first order terms of the forest canopy parameters which gives:

$$M^{o}_{\sigma f} = p_o \tag{61}$$

$$M^{o}_{\rho f} = q_o \tag{62}$$

so that Equations 52 and 53 become:

$$\sigma^{o}_{Nf} = r^{\eta} p_o N_f^{\delta} \tag{63}$$

$$\rho^{o}_{Nf} = r^{\kappa} q_o N_f^{\beta} \tag{64}$$

Therefore, within this approximation only two empirical constants, p_o and q_o, need to be determined to determine the radiance statistics of forest canopies.

4 Terrain Temperature Statistics

Average Radiance and Brightness Temperature

The following is a brief summary of the standard theory of thermal radiation (Bramson 1968; Hudson 1969). The radiance in a wave band $\Delta\lambda$ of a surface having an emissivity value ε and a physical temperature T can be obtained from the following approximate form of Planck's law (Weiss and Scoggins 1989; Weiss, Scoggins, and Meeker 1992)

$$N = \varepsilon C_1^N \, \Delta\lambda \, \lambda_{av}^{-5} \left[\exp\left(\frac{C_2^N}{\lambda_{av} T} \right) - 1 \right]^{-1} \tag{65}$$

where λ_{av} = weighted average wavelength of the thermal radiation in the wave band $\Delta\lambda$, and where

$$C_1^N = 1.192 \times 10^8 \ \mathrm{W\ \mu m^4\ m^{-2}\ sr^{-1}} \tag{66}$$

$$C_2^N = 1.4338 \times 10^4 \ \mathrm{\mu m\ K} \tag{67}$$

Equivalently, the radiance can be written in terms of the brightness temperature T_B as follows

$$N = C_1^N \, \Delta\lambda \, \lambda_{av}^{-5} \left[\exp\left(\frac{C_2^N}{\lambda_{av} \, T_B} \right) - 1 \right]^{-1} \tag{68}$$

Using Equations 65 and 68 gives the following standard results (Bramson 1968)

$$\varepsilon = \left[\exp\left(\frac{C_2^N}{\lambda_{av}\, T} \right) - 1 \right] \left[\exp\left(\frac{C_2^N}{\lambda_{av}\, T_B} \right) - 1 \right]^{-1} \tag{69}$$

$$T_B = \frac{C_2^N\, \lambda_{av}^{-1}}{\ln\left(1 + C_1^N\, \Delta\lambda\, \lambda_{av}^{-5}\, N^{-1}\right)}$$

$$= \frac{C_2^N\, \lambda_{av}^{-1}}{\ln\left\{ 1 + \varepsilon^{-1} \left[\exp\left(\frac{C_2^N}{\lambda_{av}\, T} \right) - 1 \right] \right\}} \tag{70}$$

$$T = \frac{C_2^N\, \lambda_{av}^{-1}}{\ln\left(1 + \varepsilon\, C_1^N\, \Delta\lambda\, \lambda_{av}^{-5}\, N^{-1}\right)}$$

$$= \frac{C_2^N\, \lambda_{av}^{-1}}{\ln\left\{ 1 + \varepsilon \left[\exp\left(\frac{C_2^N}{\lambda_{av}\, T_B} \right) - 1 \right] \right\}} \tag{71}$$

For the IR wave bands of interest in this report, namely 3 to 5 and 8 to 12 μm, the following Wien's law approximations to Equations 65, 68, and 69-71 are valid

$$N \sim \varepsilon\, C_1^N\, \Delta\lambda\, \lambda_{av}^{-5} \exp\left(-\frac{C_2^N}{\lambda_{av}\, T}\right)$$

$$\sim C_1^N\, \Delta\lambda\, \lambda_{av}^{-5} \exp\left(-\frac{C_2^N}{\lambda_{av}\, T_B}\right) \tag{72}$$

$$\ln \varepsilon \sim C_2^N\, \lambda_{av}^{-1}\left(\frac{1}{T} - \frac{1}{T_B}\right) \tag{73}$$

$$T_B \sim C_2^N\, \lambda_{av}^{-1}\, \ln^{-1}\left(C_1^N\, \Delta\lambda\, \lambda_{av}^{-5}\, N^{-1}\right)$$

$$\sim T\left(1 - \frac{T\, \lambda_{av}}{C_2^N} \ln \varepsilon\right)^{-1} \tag{74}$$

$$\sim T\left(1 + \frac{T\, \lambda_{av}}{C_2^N} \ln \varepsilon\right)$$

$$T \sim C_2^N\, \lambda_{av}^{-1}\, \ln^{-1}\left(\varepsilon\, C_1^N\, \Delta\lambda\, \lambda_{av}^{-5}\, N^{-1}\right)$$

$$\sim T_B\left(1 + \frac{T_B\, \lambda_{av}}{C_2^N} \ln \varepsilon\right)^{-1} \tag{75}$$

$$\sim T_B\left(1 - \frac{T_B\, \lambda_{av}}{C_2^N} \ln \varepsilon\right)$$

Equations 72-75 are only approximations.

As an example of the use of Equations 65-75, consider the 8- to 12-µm wave band. For this case, $\Delta\lambda = 4$ µm, $\lambda_{av} = 10.76$ µm and therefore

$$C_2^N \lambda_{av}^{-1} = 1332.5 \text{ K} \tag{76}$$

$$C_1^N \lambda_{av}^{-5} \Delta\lambda = 3305.8 \text{ Wm}^{-2} \text{ sr}^{-1} \tag{77}$$

so that Equation 68 gives the radiance for the 8- to 12-μm wave band as

$$\begin{aligned} N &= 3305.8 \left[\exp\left(1332.5/T_B\right) - 1\right]^{-1} \\ &\sim 3305.8 \exp\left(-1332.5/T_B\right) \end{aligned} \tag{78}$$

Now consider the example of the special case of the 3- to 5-μm wave band for which $\Delta\lambda = 2$ μm and $\lambda_{av} = 4.8$ μm so that for this case

$$C_2^N \lambda_{av}^{-1} = 2987.1 \text{ K} \tag{79}$$

$$C_1^N \lambda_{av}^{-5} \Delta\lambda = 93562.1 \text{ Wm}^{-2} \text{ sr}^{-1} \tag{80}$$

and therefore the radiance for the 3- to 5-μm wave band is given by

$$\begin{aligned} N &= 93562.1 \left[\exp\left(2987.1/T_B\right) - 1\right]^{-1} \\ &\sim 93562.1 \exp\left(-2987.1/T_B\right) \end{aligned} \tag{81}$$

The equations given above are useful expressions for the radiance of natural and man-made surfaces.

Radiance and Temperature Statistics

This section determines the relationship between the statistical parameters of the terrain radiance and the statistical parameters of brightness temperature and physical temperature of the terrain. The determination of the standard deviation of the brightness temperature in terms of the standard deviation of

the radiance is accomplished by using Planck's radiation law, which is written in the form of Equation 68. The terrain radiance calculation that includes the effects of texture can be obtained from Equation 68 as

$$N + \sigma_N = C_1^N \, \Delta\lambda \, \lambda_{av}^{-5} \left\{ \exp\left[\frac{C_2^N}{\lambda_{av}(T_B + \sigma_{TB})} \right] - 1 \right\}^{-1} \qquad (82)$$

where

σ_N = standard deviation of the terrain radiance

σ_{TB} = standard deviation of the terrain brightness temperature

Then a Taylor series expansion of Equation 82 about the temperature T_B keeping only the linear term gives the standard deviation of the radiance as

$$\sigma_N = C_1^N \, C_2^N \, \Delta\lambda \, \lambda_{av}^{-6} \, T_B^{-2} \, \sigma_{TB} \exp\left(\frac{C_2^N}{\lambda_{av} \, T_B} \right) \left[\exp\left(\frac{C_2^N}{\lambda_{av} \, T_B} \right) - 1 \right]^{-2}$$

$$= C_2^N \, \lambda_{av}^{-1} \, T_B^{-2} \, N \, \sigma_{TB} \exp\left(\frac{C_2^N}{\lambda_{av} \, T_B} \right) \left[\exp\left(\frac{C_2^N}{\lambda_{av} \, T_B} \right) - 1 \right]^{-1} \qquad (83)$$

$$= (C_1^N \, C_2^N \, \Delta\lambda)^{-1} \, \lambda_{av}^{6} \, N^2 \, \sigma_{TB} \, (1 + C_1^N \, \Delta\lambda \, \lambda_{av}^{-5} \, N^{-1}) \ln^2 (1 + C_1^N \, \Delta\lambda \, \lambda_{av}^{-5} \, N^{-1})$$

However, in the wave bands 3 to 5 and 8 to 12 μm and for $T_B \sim 300$ K, the following Wien approximation is valid

$$\exp\left(\frac{C_2^N}{\lambda_{av} \, T_B} \right) \gg 1 \qquad \text{or} \qquad C_1^N \, \Delta\lambda \, \lambda_{av}^{-5} \, N^{-1} \gg 1 \qquad (84)$$

and it follows approximately that

$$\sigma_N \sim C_1^N\ C_2^N\ \Delta\lambda\ \lambda_{av}^{-6}\ T_B^{-2}\ \sigma_{TB} \left[\exp\left(\frac{C_2^N}{\lambda_{av}\ T_B}\right) - 1 \right]^{-1}$$

$$\sim C_1^N\ C_2^N\ \Delta\lambda\ \lambda_{av}^{-6}\ T_B^{-2}\ \sigma_{TB} \exp\left(-\frac{C_2^N}{\lambda_{av}\ T_B}\right) \tag{85}$$

$$\sim C_2^N\ \lambda_{av}^{-1}\ T_B^{-2}\ N\ \sigma_{TB}$$

$$\sim \left(C_2^N\right)^{-1} \lambda_{av}\ N\ \ln^2\left(C_1^N\ \Delta\lambda\ \lambda_{av}^{-5}\ N^{-1}\right) \sigma_{TB}$$

Equations 83-87 can be used to calculate the standard deviation of the brightness temperature σ_{TB} in terms of the standard deviation of the radiance. For example Equation 83 gives

$$\sigma_{TB} = \left(C_1^N\ C_2^N\ \Delta\lambda\right)^{-1} \lambda_{av}^6\ T_B^2\ \sigma_N \exp\left(-\frac{C_2^N}{\lambda_{av}\ T_B}\right)\left[\exp\left(\frac{C_2^N}{\lambda_{av}\ T_B}\right) - 1\right]^2$$

$$= \left(C_2^N\right)^{-1} \lambda_{av}\ T_B^2\ N^{-1}\ \sigma_N \exp\left(-\frac{C_2^N}{\lambda_{av}\ T_B}\right)\left[\exp\left(\frac{C_2^N}{\lambda_{av}\ T_B}\right) - 1\right] \tag{86}$$

$$= C_1^N\ C_2^N\ \Delta\lambda\ \lambda_{av}^{-6}\ N^{-2}\ \sigma_N\ (1 + C_1^N\ \Delta\lambda\ \lambda_{av}^{-5}\ N^{-1})^{-1} \ln^{-2}$$

$$(1 + C_1^N\ \Delta\lambda\ \lambda_{av}^{-5}\ N^{-1})$$

while the approximate Equation 85 gives

$$
\begin{aligned}
\sigma_{TB} &\sim \left(C_1^N\ C_2^N\ \Delta\lambda\right)^{-1}\ \lambda_{av}^6\ T_B^2 \left[\exp\left(\frac{C_2^N}{\lambda_{av}\ T_B}\right) - 1\right] \sigma_N \\
&\sim \left(C_1^N\ C_2^N\ \Delta\lambda\right)^{-1}\ \lambda_{av}^6\ T_B^2\ \exp\left(\frac{C_2^N}{\lambda_{av}\ T_B}\right) \sigma_N \\
&\sim \left(C_2^N\right)^{-1}\ \lambda_{av}\ T_B^2\ N^{-1}\ \sigma_N \\
&\sim C_2^N\ \lambda_{av}^{-1}\ N^{-1}\ \ln^{-2}\left(C_1^N\ \Delta\lambda\ \lambda_{av}^{-5}\ N^{-1}\right) \sigma_N
\end{aligned}
\tag{87}
$$

For the 8- to 12-µm wave band, Equation 87 becomes

$$
\begin{aligned}
\sigma_{TB} &\sim 2.27 \times 10^{-7}\ T_B^2 \left[\exp\left(1332.5/T_B\right) - 1\right] \sigma_N \\
&\sim 2.27 \times 10^{-7}\ T_B^2\ \exp\left(1332.5/T_B\right) \sigma_N \\
&\sim 7.50 \times 10^{-4}\ T_B^2\ N^{-1}\ \sigma_N \\
&\sim 1332.5\ N^{-1}\ \ln^{-2}\left(3305.8/N\right) \sigma_N
\end{aligned}
\tag{88}
$$

while for the 3- to 5-µm wave band, Equation 87 gives

$$
\begin{aligned}
\sigma_{TB} &\sim 3.58 \times 10^{-9}\ T_B^2 \left[\exp\left(2987.1/T_B\right) - 1\right] \sigma_N \\
&\sim 3.58 \times 10^{-9}\ T_B^2\ \exp\left(2987.1/T_B\right) \sigma_N \\
&\sim 3.35 \times 10^{-4}\ T_B^2\ N^{-1}\ \sigma_N \\
&\sim 2987.1\ N^{-1}\ \ln^{-2}\left(93562.1/N\right) \sigma_N
\end{aligned}
\tag{89}
$$

These equations establish the relationship between the standard deviation of the radiance and the standard deviation of the brightness temperature.

The standard deviation of the radiance can also be expressed in terms of the standard deviation of the emissivity and the standard deviation of the physical temperature by using Equation 65 which gives

$$N + \sigma_N = (\varepsilon + \sigma_\varepsilon)\, C_1^N\, \Delta\lambda\, \lambda_{av}^{-5} \left\{ \exp\left[\frac{C_2^N}{\lambda_{av}\,(T + \sigma_T)}\right] - 1 \right\}^{-1} \tag{90}$$

A Taylor series expansion of Equation 90 keeping only the linear terms gives the following results

$$\sigma_N = C_1^N\, \Delta\lambda\, \lambda_{av}^{-5}\, \sigma_\varepsilon \left[\exp\left(\frac{C_2^N}{\lambda_{av}\, T}\right) - 1\right]^{-1}$$

$$+\, \varepsilon\, C_1^N\, C_2^N\, \Delta\lambda\, \lambda_{av}^{-6}\, T^{-2}\, \sigma_T\, \exp\left(\frac{C_2^N}{\lambda_{av}\, T}\right)\left[\exp\left(\frac{C_2^N}{\lambda_{av}\, T}\right) - 1\right]^{-2} \tag{91}$$

which can also be written as

$$\sigma_N = N\varepsilon^{-1}\sigma_\varepsilon + C_2^N\, \lambda_{av}^{-1}\, T^{-2}\, N\sigma_T\, \exp\left(\frac{C_2^N}{\lambda_{av}\, T}\right)\left[\exp\left(\frac{C_2^N}{\lambda_{av}\, T}\right) - 1\right]^{-1}$$

$$= N\varepsilon^{-1}\sigma_\varepsilon + (\varepsilon\, C_1^N\, C_2^N\, \Delta\lambda)^{-1}\, \lambda_{av}^{6}\, N^2\, \sigma_T\, (1 + \varepsilon\, C_1^N\, \Delta\lambda\, \lambda_{av}^{-5}\, N^{-1})$$

$$\ln^2 (1 + \varepsilon\, C_1^N\, \Delta\lambda\, \lambda_{av}^{-5}\, N^{-1}) \tag{92}$$

In a manner similar to that shown in Equation 84, the following inequalities are valid for the 3- to 5- and 8- to 12-µm wave bands

$$\exp\left(\frac{C_2^N}{\lambda_{av}\ T}\right) \gg 1 \qquad \text{or} \qquad \varepsilon\ C_1^N\ \Delta\lambda\ \lambda_{av}^{-5}\ N^{-1} \gg 1 \tag{93}$$

so that the Wien approximations to Equations 91 and 92 are

$$\begin{aligned}
\sigma_N &\sim \varepsilon\ C_1^N \Delta\lambda\ \lambda_{av}^{-5} \left(\varepsilon^{-1}\sigma_\varepsilon + C_2^N\ \lambda_{av}^{-1}\ T^{-2}\ \sigma_T\right)\left[\exp\left(\frac{C_2^N}{\lambda_{av}\ T}\right) - 1\right]^{-1} \\
&= N\left(\varepsilon^{-1}\sigma_\varepsilon + C_2^N\ \lambda_{av}^{-1}\ T^{-2}\ \sigma_T\right) \\
&\sim N\left[\varepsilon^{-1}\sigma_\varepsilon + \left(C_2^N\right)^{-1} \lambda_{av}\ \ln^2\left(\varepsilon\ C_1^N\ \Delta\lambda\ \lambda_{av}^{-5}\ N^{-1}\right)\sigma_T\right]
\end{aligned} \tag{94}$$

Equations 91-94 relate σ_N, σ_T and, σ_ε.

Equations 83-85 and 91-94 can be used to estimate the standard deviation of the emissivity. A comparison of Equations 83 and 92 gives

$$\begin{aligned}
\sigma_\varepsilon/\varepsilon &= C_2^N\ \lambda_{av}^{-1} \left\{ T_B^{-2}\ \sigma_{TB}\ \exp\left(\frac{C_2^N}{\lambda_{av}\ T_B}\right)\left[\exp\left(\frac{C_2^N}{\lambda_{av}\ T_B}\right) - 1\right]^{-1} \right. \\
&\qquad \left. - T^{-2}\ \sigma_T\ \exp\left(\frac{C_2^N}{\lambda_{av}\ T}\right)\left[\exp\left(\frac{C_2^N}{\lambda_{av}\ T}\right) - 1\right]^{-1} \right\} \\
&= \left(C_1^N\ C_2^N\ \Delta\lambda\right)^{-1} \lambda_{av}^6\ N \left[\sigma_{TB}\left(1 + C_1^N\ \Delta\lambda\ \lambda_{av}^{-5}\ N^{-1}\right)\ln^2\left(1 + C_1^N\ \Delta\lambda\ \lambda_{av}^{-5}\ N^{-1}\right)\right. \\
&\qquad - \varepsilon^{-1}\sigma_T\left(1 + \varepsilon\ C_1^N\ \Delta\lambda\ \lambda_{av}^{-5}\ N^{-1}\right)\ln^2 \\
&\qquad \left.\left(1 + \varepsilon\ C_1^N\ \Delta\lambda\ \lambda_{av}^{-5}\ N^{-1}\right)\right]
\end{aligned} \tag{95}$$

Combining the Wien approximations of Equations 84 and 93 with Equation 95 gives

$$
\begin{aligned}
\sigma_\varepsilon/\varepsilon &\sim C_2^N \lambda_{av}^{-1} \left(T_B^{-2}\, \sigma_{TB} - T^{-2}\, \sigma_T\right) \\
&\sim \left(C_2^N\right)^{-1} \lambda_{av} \Big[\sigma_{TB} \ln^2 \left(C_1^N\, \Delta\lambda\, \lambda_{av}^{-5}\, N^{-1}\right) \\
&\quad - \sigma_T \ln^2 \left(\varepsilon\, C_1^N\, \Delta\lambda\, \lambda_{av}^{-5}\, N^{-1}\right)\Big]
\end{aligned}
\tag{96}
$$

Equation 96 can be used to estimate σ_ε but requires that measurements of σ_T be available, which are generally difficult to obtain. A more useful expression can be obtained from Equation 96 by assuming the approximation

$$
\sigma_T \sim \sigma_{TB} \tag{97}
$$

Combining Equations 96 and 97 gives

$$
\begin{aligned}
\sigma_\varepsilon/\varepsilon &\sim C_2^N \lambda_{av}^{-1} \left(T_B^{-2} - T^{-2}\right) \sigma_{TB} \\
&\sim \left(C_2^N\right)^{-1} \lambda_{av} \left[\ln^2 \left(C_1^N\, \Delta\lambda\, \lambda_{av}^{-5}\, N^{-1}\right) - \ln^2 \left(\varepsilon\, C_1^N\, \Delta\lambda\, \lambda_{av}^{-5}\, N^{-1}\right)\right] \sigma_{TB} \\
&\sim - \left(C_2^N\right)^{-1} \lambda_{av} \left[\ln^2 \varepsilon + 2 \ln \varepsilon \ln \left(C_1^N\, \Delta\lambda\, \lambda_{av}^{-5}\, N^{-1}\right)\right] \sigma_{TB} \\
&\sim -2 \ln \varepsilon \left(C_2^N\right)^{-1} \lambda_{av} \ln \left(C_1^N\, \Delta\lambda\, \lambda_{av}^{-5}\, N^{-1}\right) \sigma_{TB}
\end{aligned}
\tag{98}
$$

Combining Equations 74 and 98 gives

$$
\sigma_\varepsilon \sim -2\varepsilon \ln \varepsilon\, T_B^{-1}\, \sigma_{TB} \tag{99}
$$

Equation 99 shows that for natural terrain materials with $T_B \sim 300K$, $\sigma_{TB} \sim 1K$, and a range of values of emissivity given by $0.1 < \varepsilon < 0.98$, the corresponding range of σ_ε is given by

$$6.8 \times 10^{-4} < \sigma_\varepsilon < 1.5 \times 10^{-3} \tag{100}$$

which is a spread of only a factor of two.

Finally, the relationship between the correlation lengths of the radiance, the physical temperature, and the brightness temperature is given by

$$\rho_N = \rho_T = \rho_{TB} \tag{101}$$

where

ρ_N = correlation length of the terrain radiance

ρ_T = correlation length of the physical temperature

ρ_{TB} = correlation length of the brightness temperature

5 Determination of Empirical Constants of the Model

Empirical Description of Texture

The computer model WESTHERM uses heat budget algorithms to predict the radiances of various types of materials usually found in an outdoor thermal scene. Types of materials might be as follows: bare soil, green vegetation, brown vegetation, bare rock, forest canopy, etc. Each of these material types can have many varieties. For example, bare soil may have many different compositions, with different thermal properties. Similarly, green vegetation may consist of grass, tall weeds, or bushes, each with different thermal properties. Forest canopies may be of decidous trees or evergreen trees, each with different thermal properties, depending upon the season of the year. The purpose of algorithms, such as WESTHERM, is to predict the radiance of a given material over a diurnal cycle, given the geographical location and the day of the year. The problem is that these programs predict only the average radiances of the material under a given set of circumstances. In the real world, there is a natural fluctuation about the average—the radiance of a material is said to have texture. This texture is customarily measured in terms of two texture parameters—standard deviation and correlation length.

The standard deviation is the usual statistical parameter computed about the mean value of the radiance over a region composed of the same material type. The correlation length is defined in terms of the autocovariance function (the Fourier transform of the power spectrum) of the radiance over a region composed of the same material type. This is assumed to be identical to the linear autocorrelation coefficient (also called Pearson's r). The linear autocorrelation coefficient of a series x_i is defined by the equation

$$\check{r}(t)=\frac{\sum (x_i-\bar{x})(x_{i-t}-\bar{x})}{\sqrt{\sum (x_i-\bar{x})^2}\sqrt{\sum (x_{i-t}-\bar{x})^2}} \tag{102}$$

The function $\check{r}(t)$ is assumed to be exponential of the form $y = \exp(-t/\rho)$, where ρ is the correlation length of the series x_i. Strictly speaking, this is not

true, since $\check{r}$ has a range from -1 to 1, and the exponential function is always positive. So it is assumed that $\check{r}(t)$ can be approximated by the exponential function on the interval $0 \leq t \leq \rho$.

Power Law Model

The physics-based model of the IR radiance statistics for terrain includes several constants that have to be determined empirically from measured IR images of terrain areas that include bare soil, grass, and forested canopies for which the physical parameters and local weather conditions are known. A statistical analysis of these IR images yields the average, standard deviation, and correlation length of the radiance corresponding to known time of day, terrain characteristics, and weather conditions. The physics-based radiance statistics model is then fit to these statistical parameters, and the unknown constants of the model are determined.

The assumption upon which the texture parameter model is based is that both the standard deviation and the correlation length of radiance can be approximated by a power law. That is, if N represents radiance, and r is the camera resolution, and σ_N and ρ_N represent standard deviation and correlation length of radiance, respectively, then it is assumed that these quantities can be approximated by the equations

$$\sigma_N = bR^{\eta}n^{\delta} \tag{103}$$

and

$$\rho_N = cR^{\kappa}n^{\beta} \tag{104}$$

where b,c δ and β are model constants which must be determined by a statistical analysis of measured data, and κ and η are empirically determined constants. The current working hypothesis is that $\kappa = -1$ and $\eta = 1$. This model uses the normalized radiance obtained by dividing the radiance by the average radiance over a diurnal cycle. The normalized radiance is given by

$$n = \frac{N}{N_{av}} \tag{105}$$

where N_{av} is the average radiance over a diurnal cycle. In the same manner, the normalized resolution is written as

$$R = \frac{r}{r_{ref}} \tag{106}$$

where r_{ref} a reference resolution which in this report is chosen to have the value r_{ref} = 1.0 pixel/m. In this way, the coefficients b, δ, c and β refer to normalized radiances and normalized resolutions so that the dimensions of b and c are given by

$$[b] = Wm^{-2}sr^{-1} \qquad [c] = m \tag{107}$$

A collection of computer programs, referred to collectively as WESTEX have been developed to empirically determine the model constants and then predict the diurnal variation of the terrain texture through the use of WESTHERM. A listing of the WESTEX modules appears in Appendix A.

Yuma, AZ, Data

In the spring of 1993, data were collected at Yuma, AZ, in the form of IR images of desert scenes. These images were taken once or twice an hour over a period of days. Figures 2-7 give the measured diurnal variations of the average radiance, standard deviation of the radiance, and correlation length of the radiance. These data are obtained from measured IR images of terrain that were acquired at the Yuma, AZ, test site in the 8- to 12-µm wave band for soil areas with soil and grass mixtures (Rivera 1994a). Two of these diurnal cycles were selected for analysis. The diurnal cycles covered the time period from midnight to midnight for the dates April 8 and April 26, 1993. The terrain at the Yuma test area consists of several identifiable materials, including desert pavement and mixed grass/bare soil. For each material, and for each image, the average radiance, standard deviation of radiance, and correlation length of radiance were computed. Figures 8-13 show the average radiance, standard deviation of the radiance, and correlation length of the radiance as a function of time for the 2 days of measured data that were used in this report. Figures 14 and 15 show the measured values of the standard deviation of the radiance and the correlation length of the radiance versus the measured values of the average radiance for 2 days of data collection, while Figures 16 and 17 show the measured values of the standard deviation and correlation length versus the normalized values of the average radiance. Figures 14-17 show that the power law assumptions given by Equations 103 and 104 are not valid for the full range of the average radiance that occurs during a diurnal cycle.

It was found necessary to divide the day into seven time zones, and the measured standard deviations and correlation lengths of the radiance were fit in each zone by the method of least squares to the measured normalized radiances using Equations 103 and 104 and using the data represented in Figures 16 and 17. The results appear in Figures 18-21, which show the least square fits of

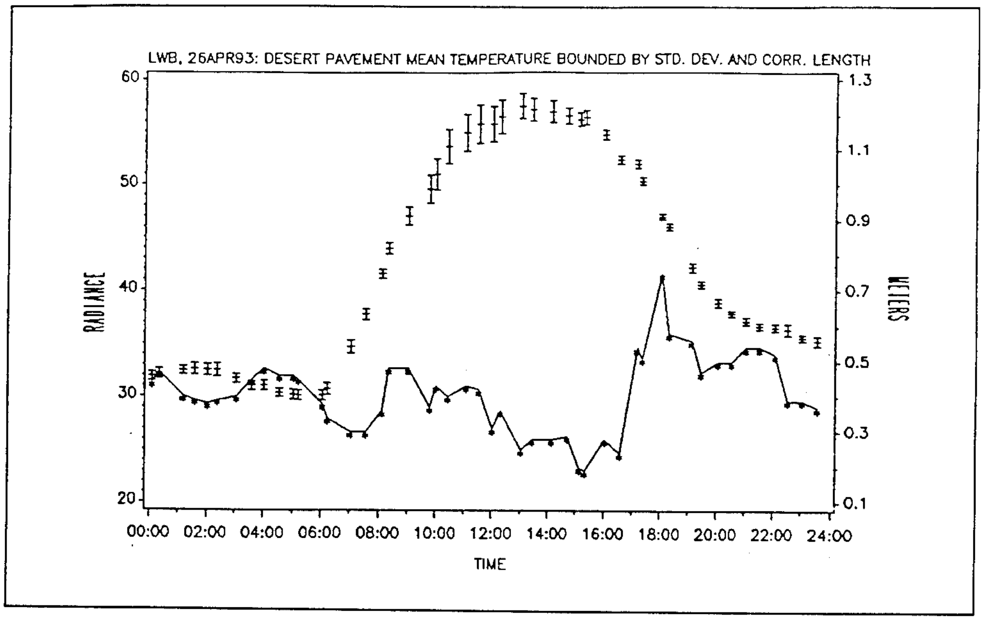

Figure 2. Measured values of the diurnal variation of the average, standard deviation, and correlation length of the radiance for desert pavement at Yuma Test Site on 24 March 1993

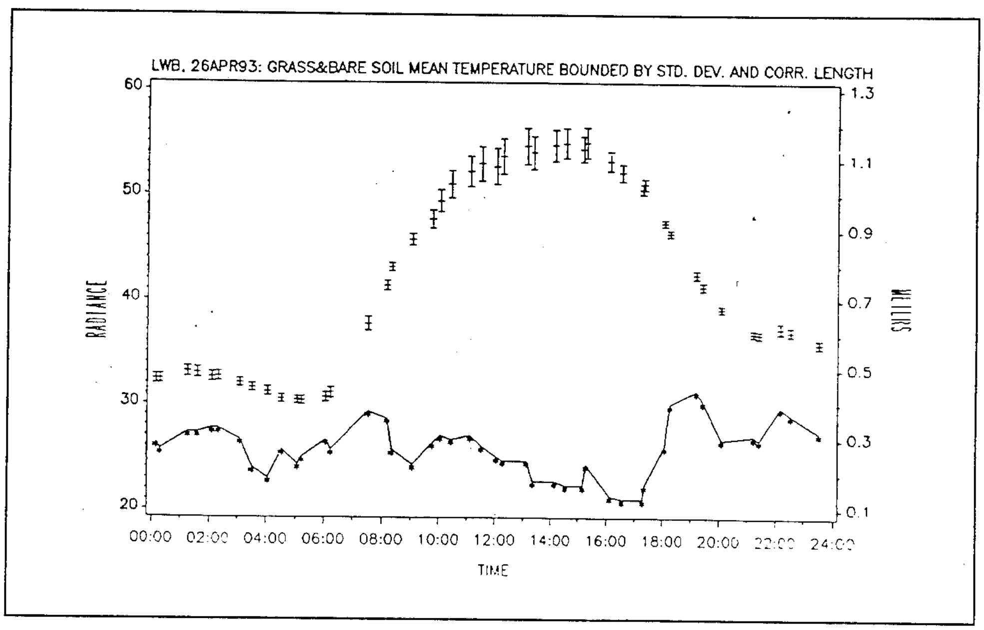

Figure 3. Measured values of the diurnal variation of the average, standard deviation, and correlation length of the radiance for grass and bare soil at Yuma Test Site on 24 March 1993

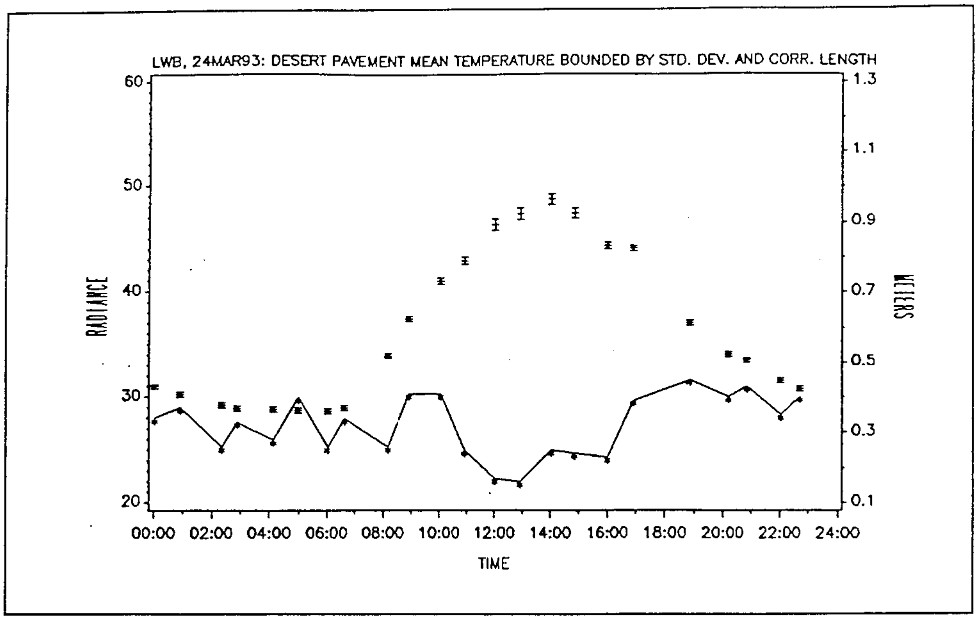

Figure 4. Measured values of the diurnal variation of the average, standard deviation, and correlation length of the radiance for desert pavement at Yuma Test Site on 8 April 1993

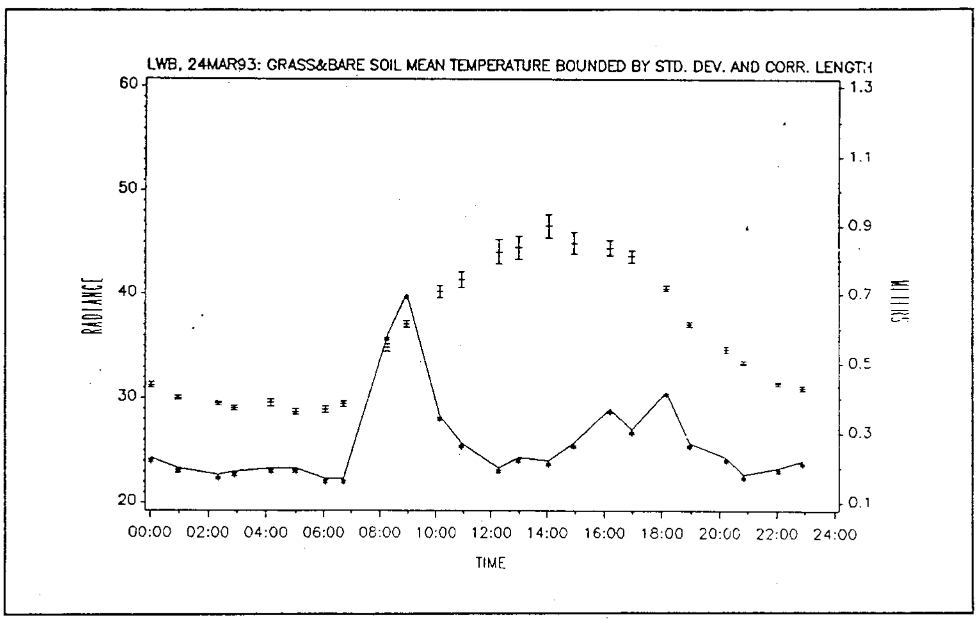

Figure 5. Measured values of the diurnal variation of the average, standard deviation, and correlation length of the radiance for grass and bare soil at Yuma Test Site on 8 April 1993

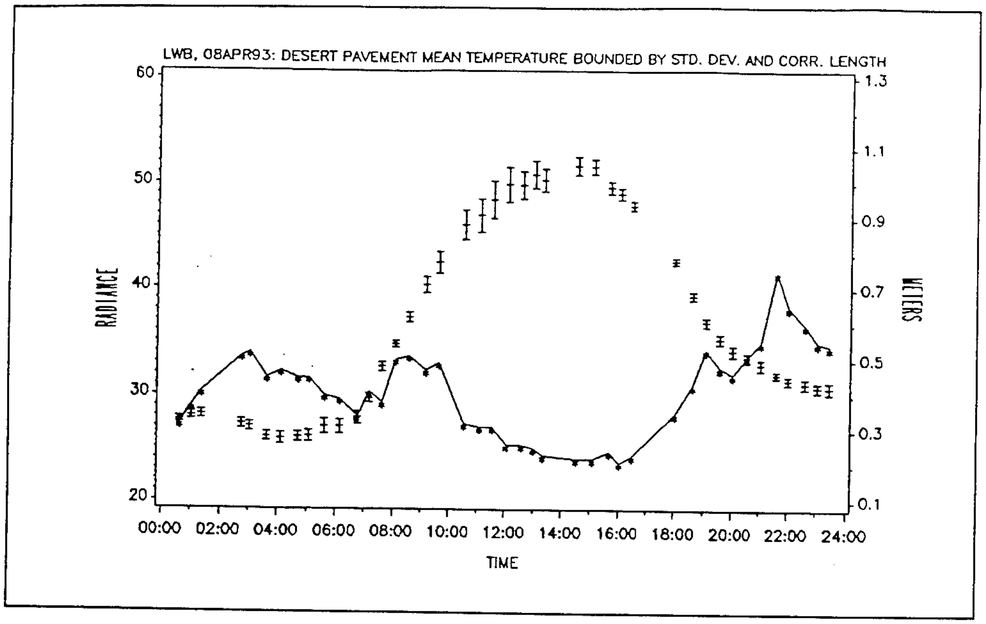

Figure 6. Measured values of the diurnal variation of the average, standard deviation, and correlation length of the radiance for desert pavement at Yuma Test Site on 26 April 1993

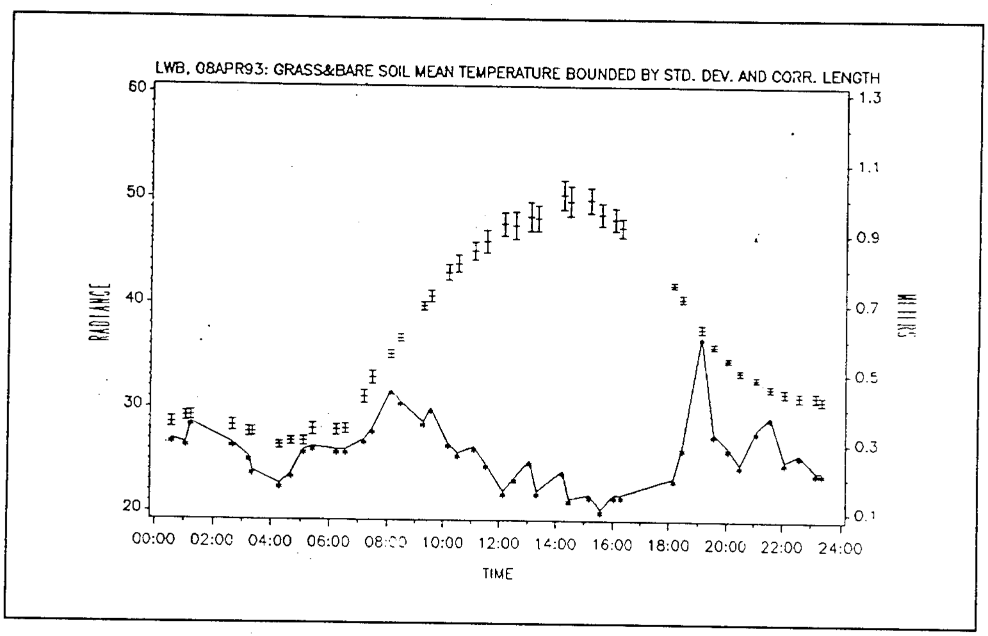

Figure 7. Measured values of the diurnal variation of the average, standard deviation, and correlation length of the radiance for grass and bare soil at Yuma Test Site on 26 April 1993

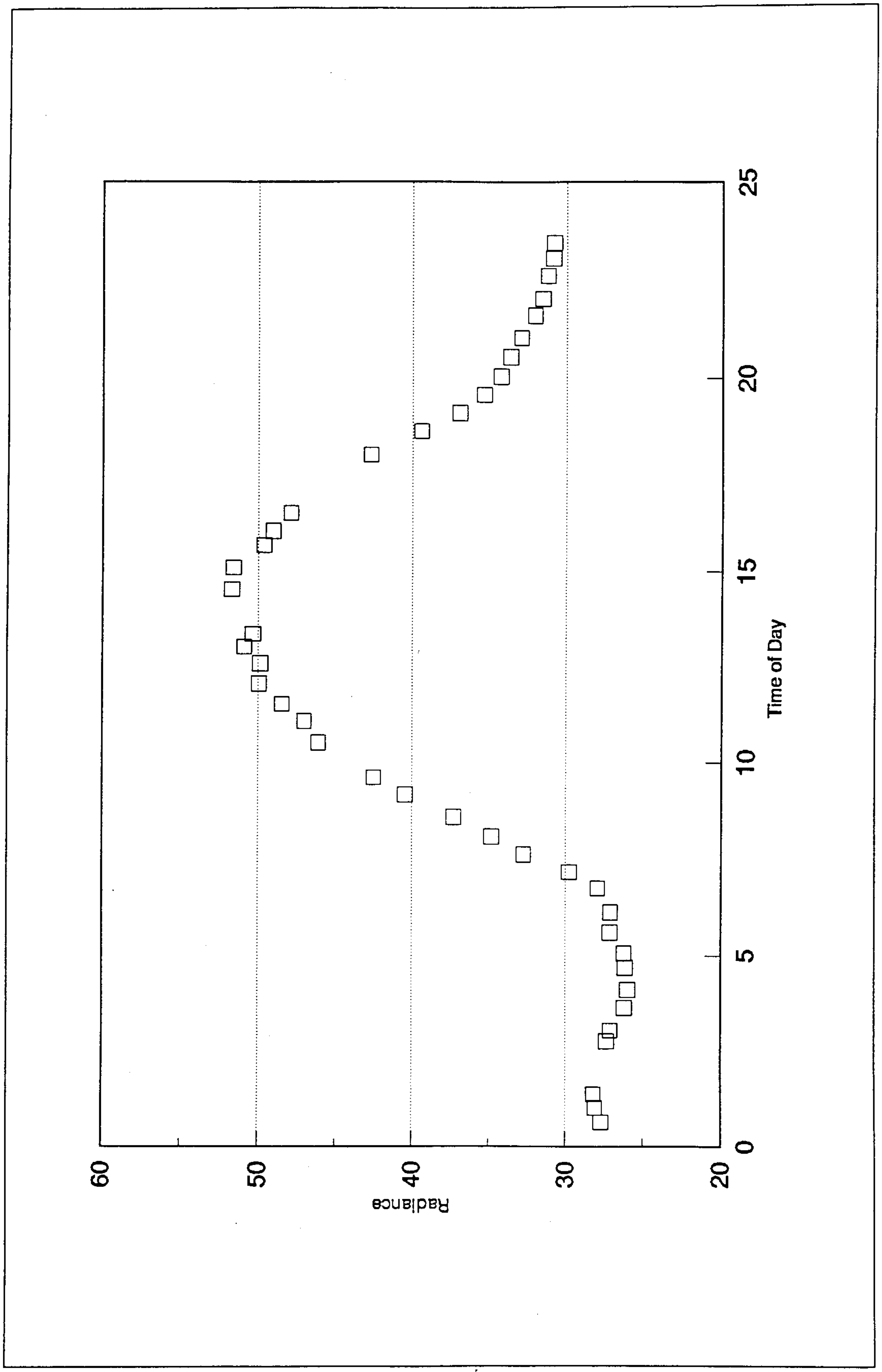

Figure 8. Measured diurnal variation of the radiance for desert pavement at Yuma, AZ, on 8 April 1993

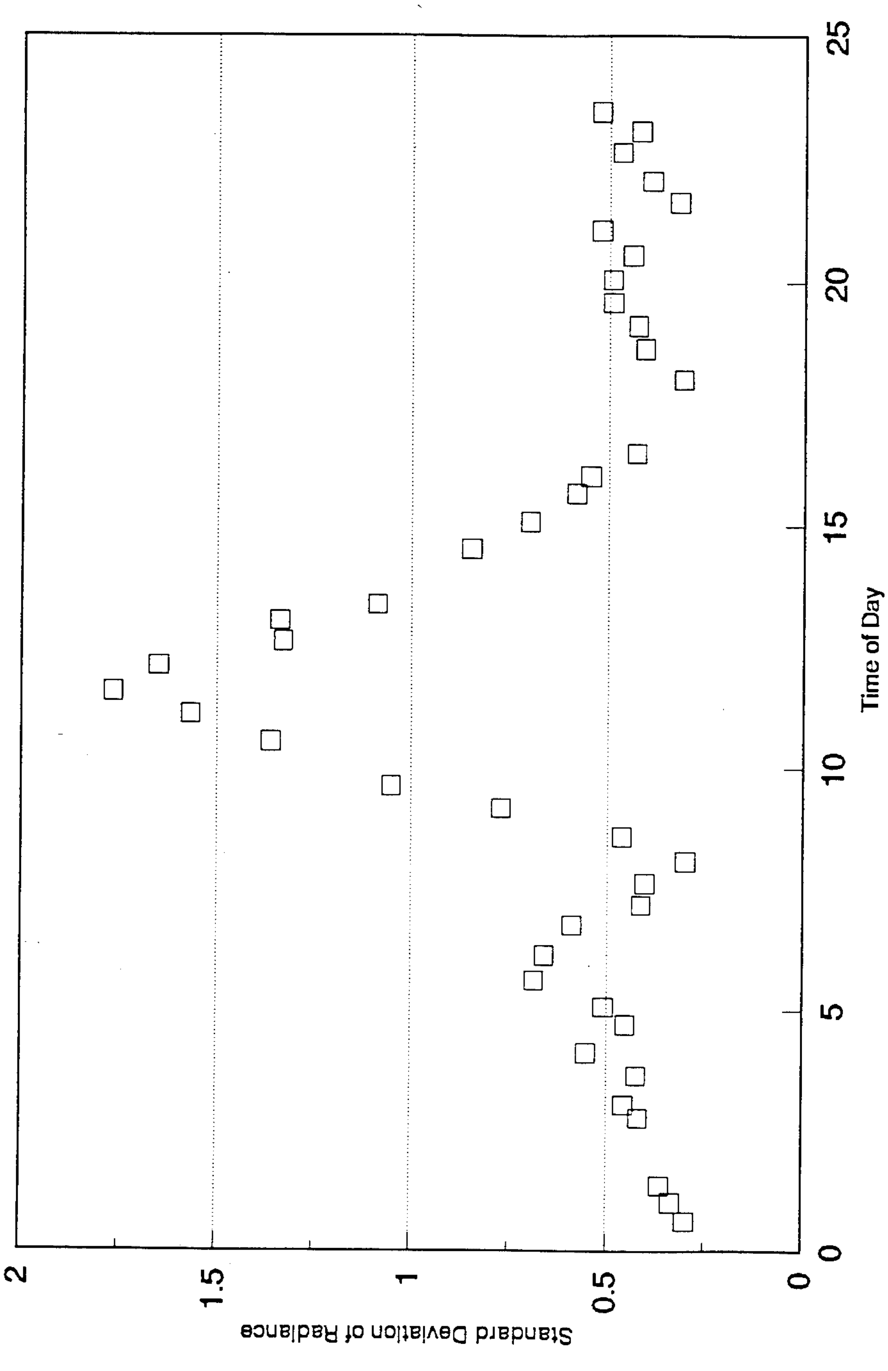

Figure 9. Measured diurnal variation of the standard deviation of the radiance for desert pavement at Yuma, AZ, on 8 April 1993

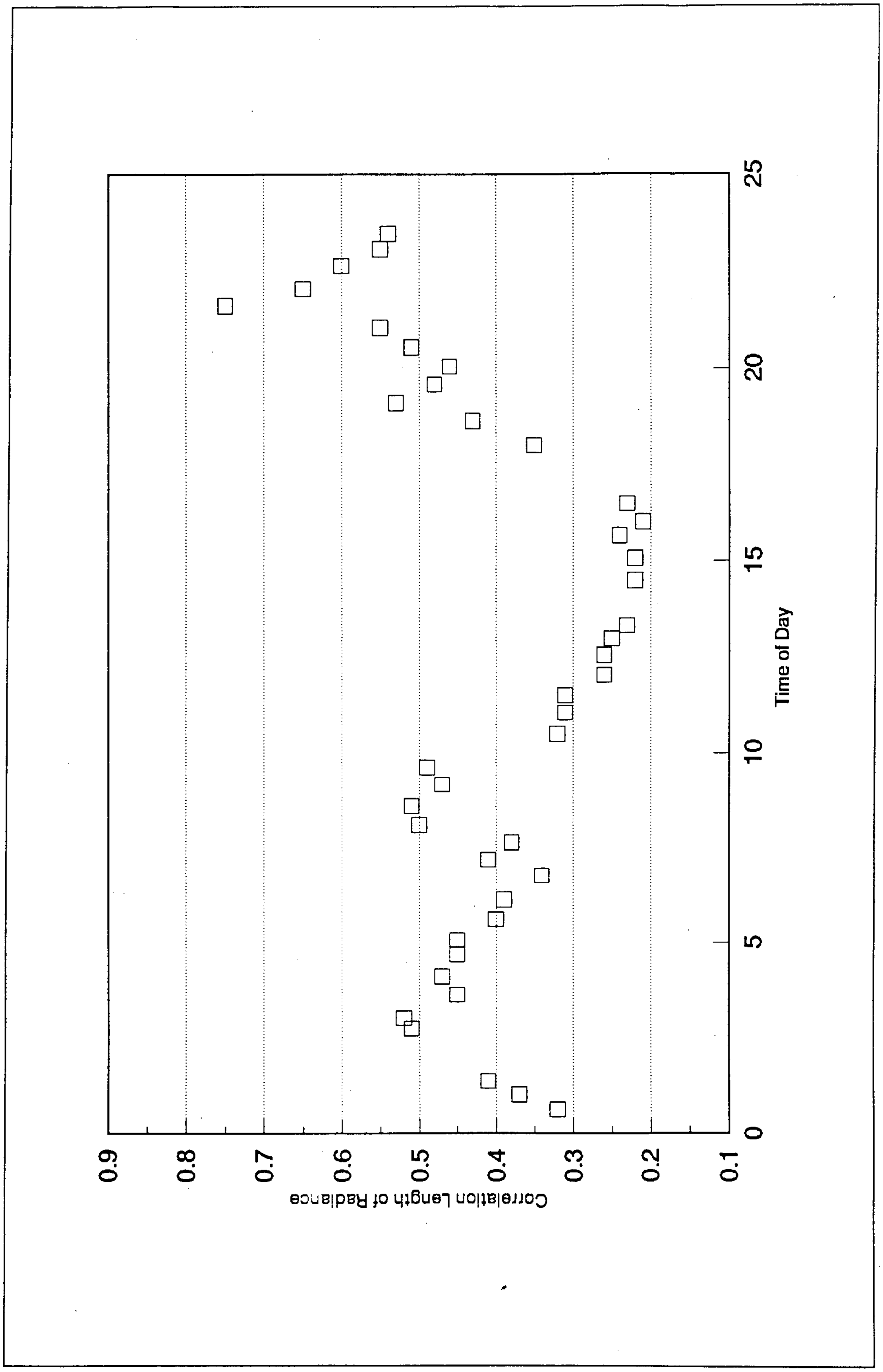

Figure 10. Measured diurnal variation of the correlation length of the radiance for desert pavement at Yuma, AZ, on 8 April 1993

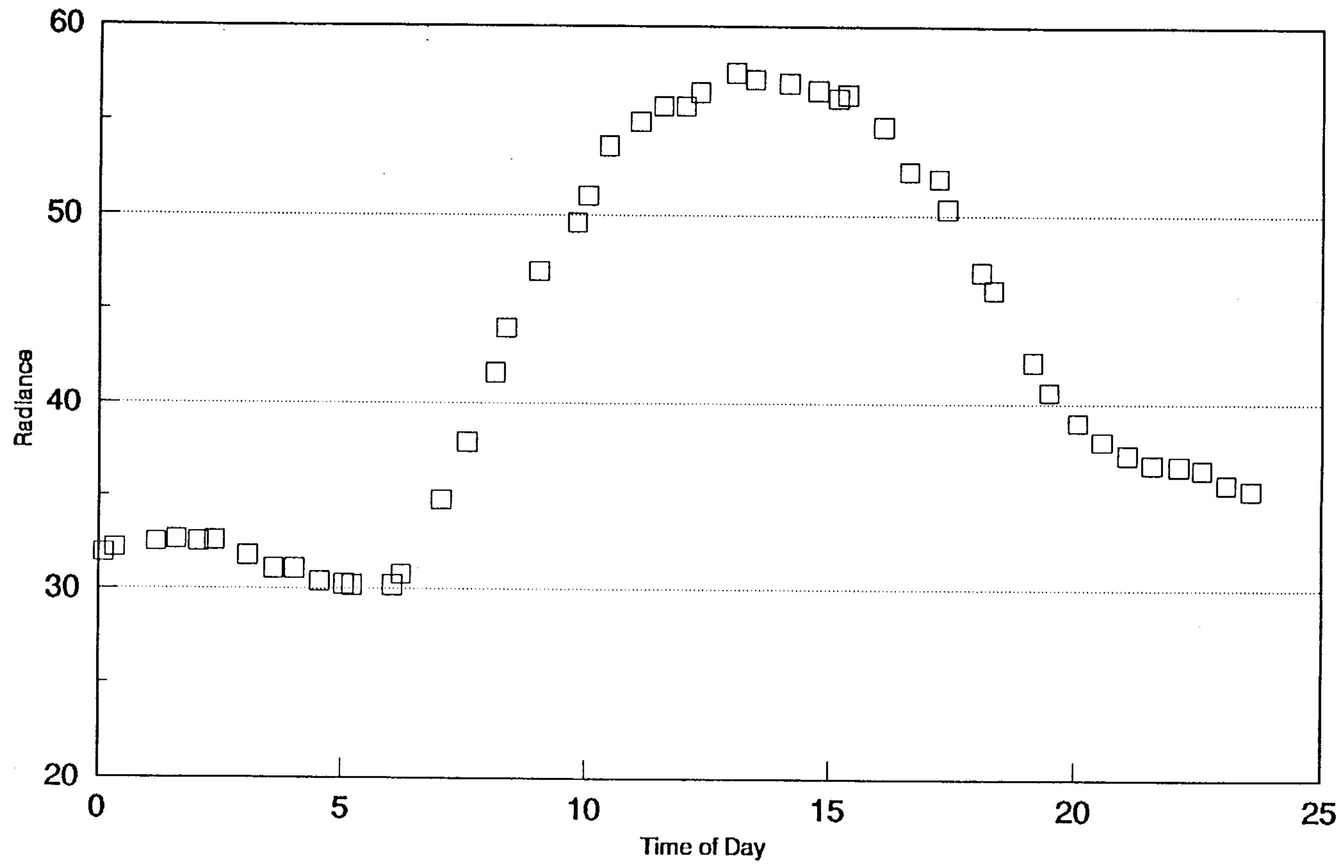

Figure 11. Measured diurnal variation of the radiance for desert pavement at Yuma, AZ, on 26 April 1993

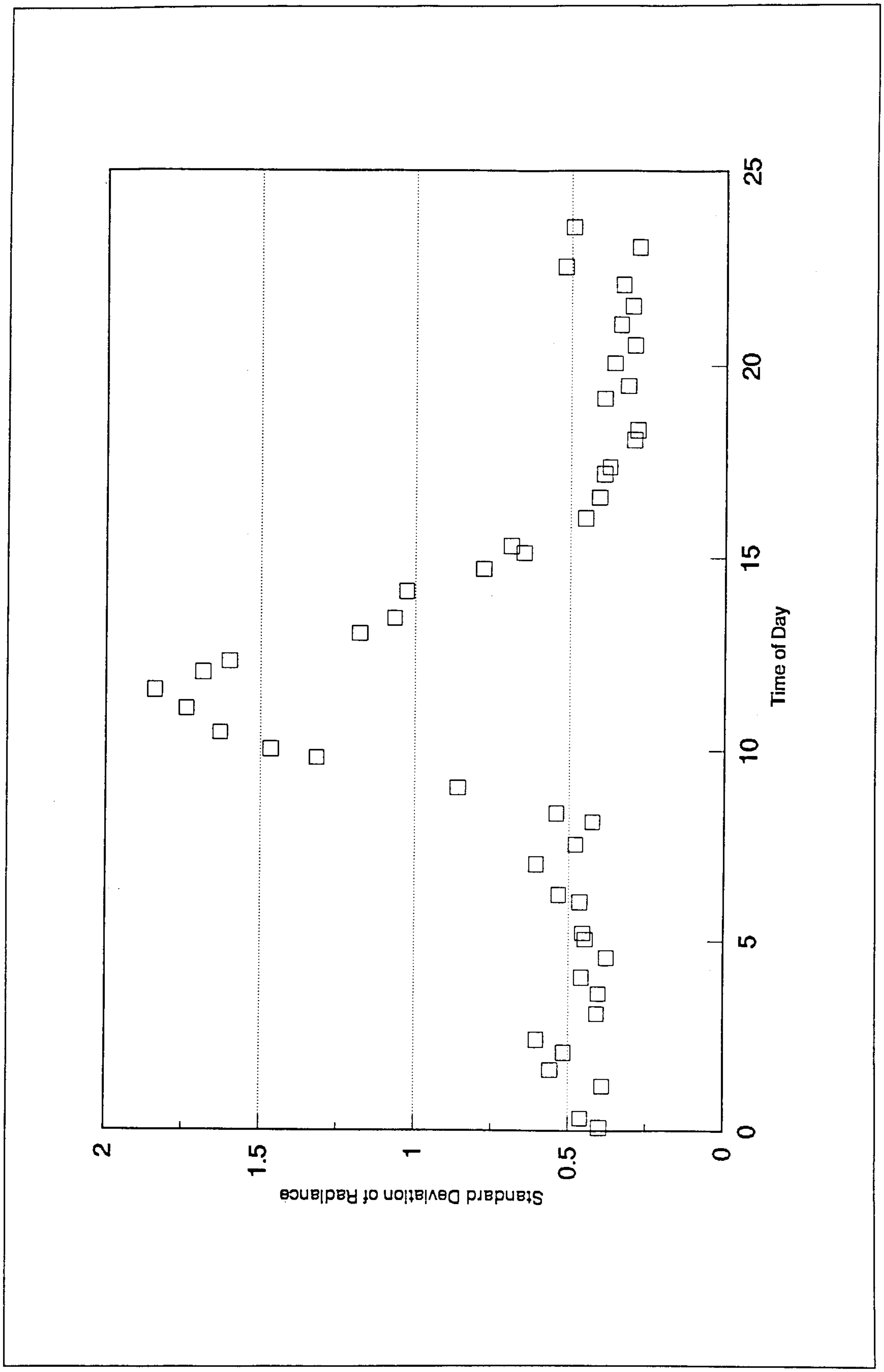

Figure 12. Measured diurnal variation of the standard deviation of the radiance for desert pavement at Yuma, AZ, on 26 April 1993

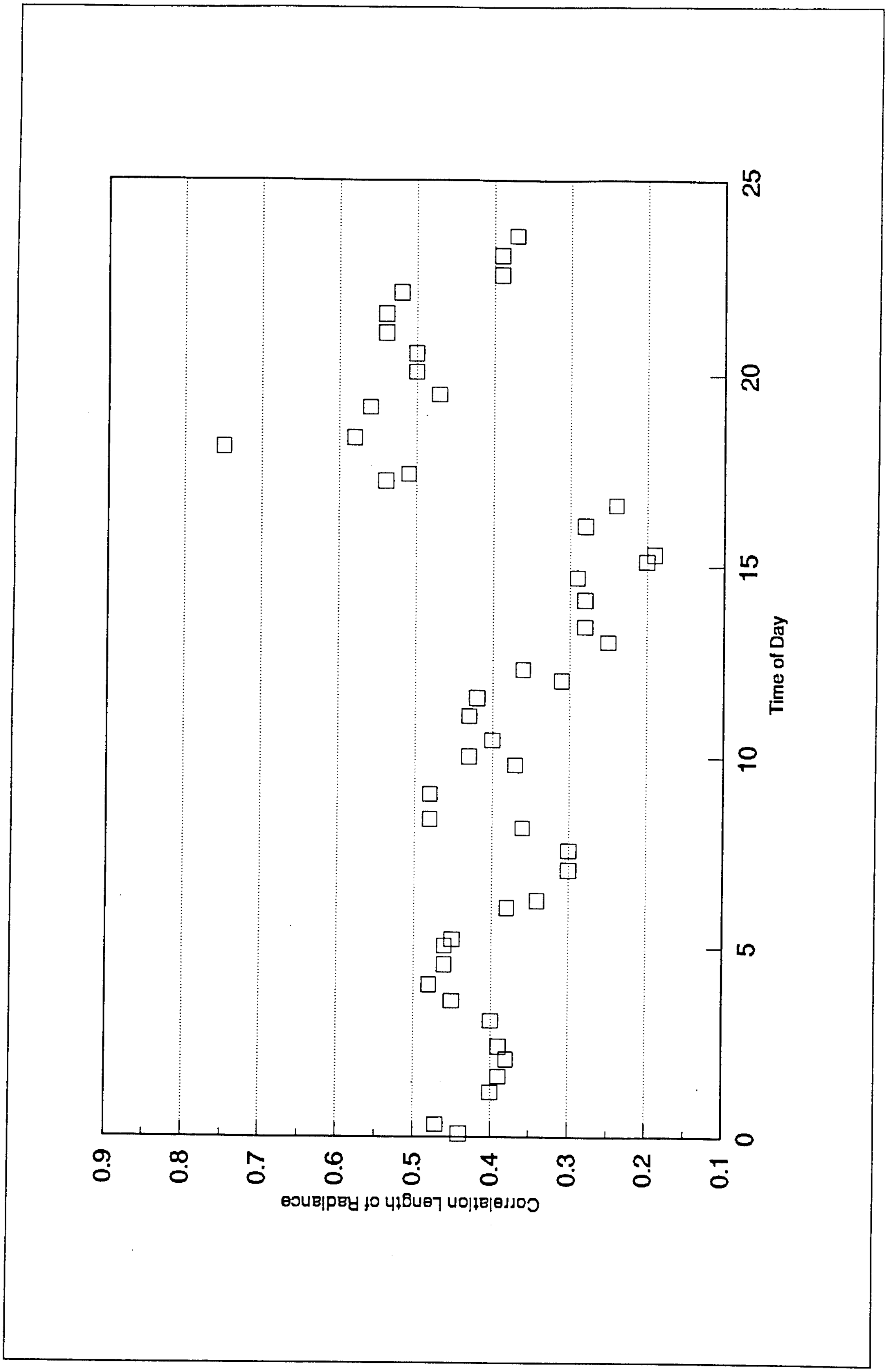

Figure 13. Measured diurnal variation of the correlation length of the radiance for desert pavement at Yuma, AZ, on 26 April 1993

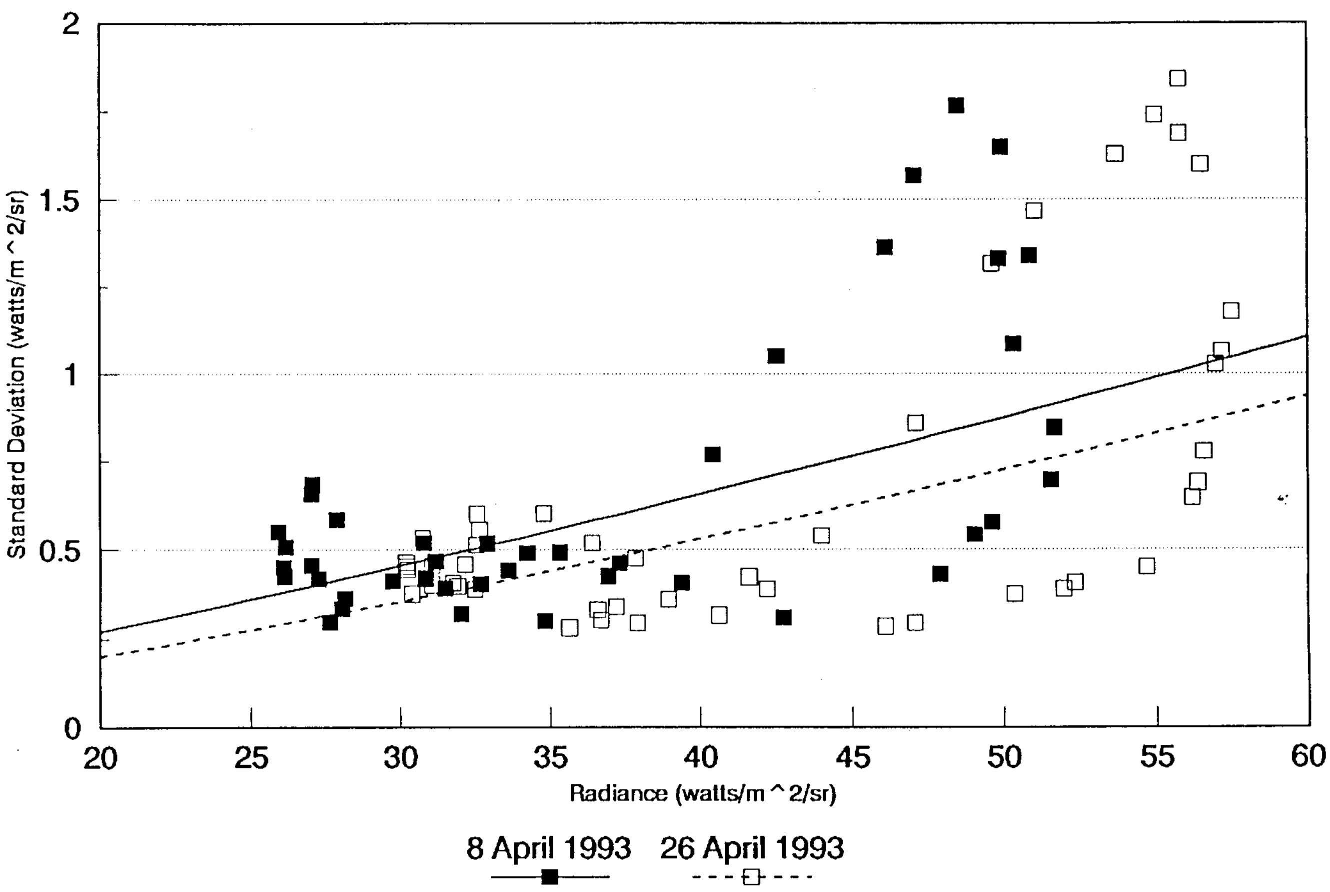

Figure 14. A comparison of the measured standard deviation of the radiance with the measured radiance for desert pavement at Yuma, AZ, on 8 April 1993 and 26 April 1993. The solid and dotted lines are best fit power laws that indicate that this description is not adequate to describe the 24-hr diurnal variation

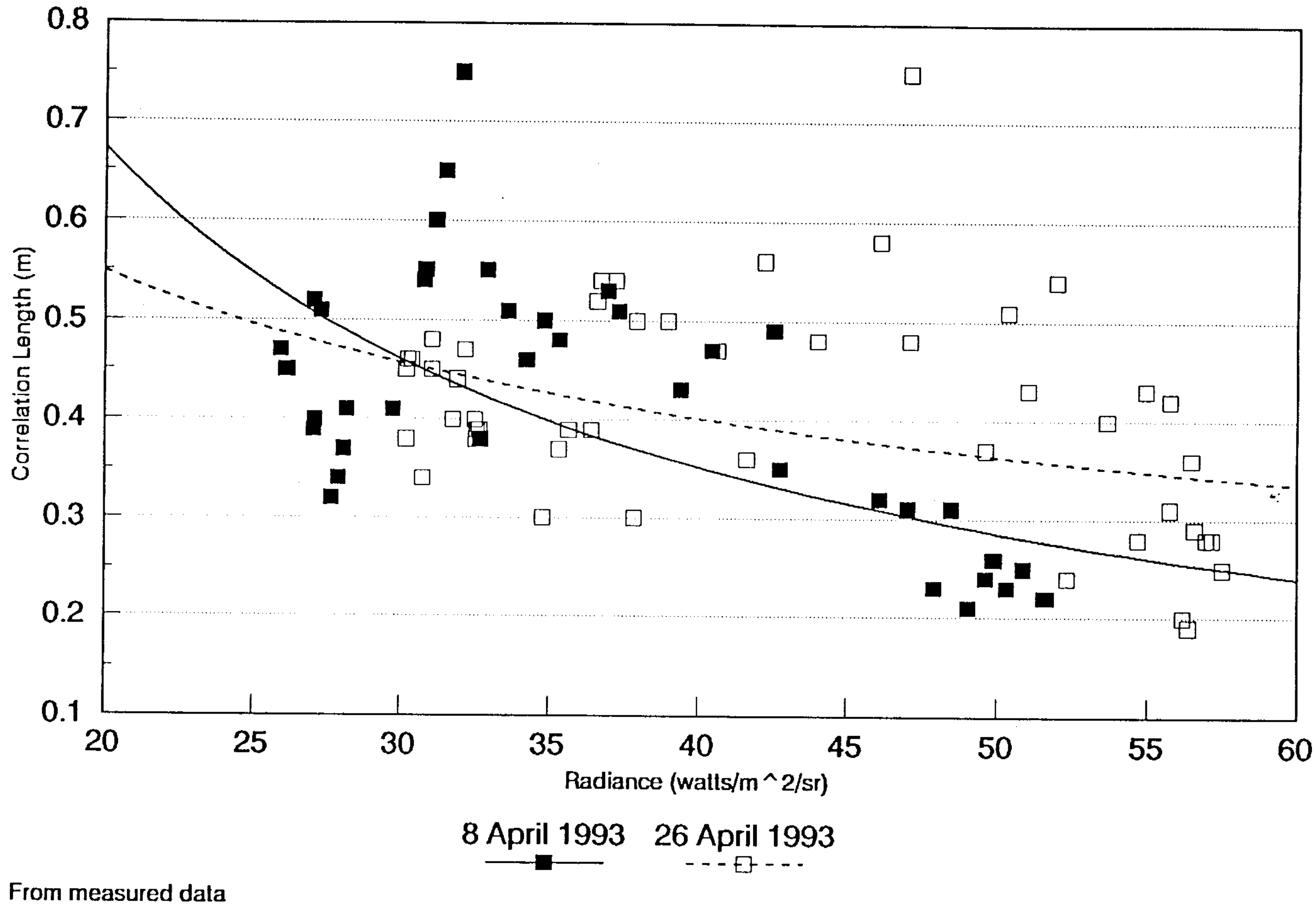

Figure 15. A display of the measured correlation length of the radiance versus the measured radiance for desert pavement at Yuma, AZ, on 8 April and 26 April 1993. The solid and dotted lines represent a power law fit to the data and show that the 24-hr diurnal variation is not describable by this means

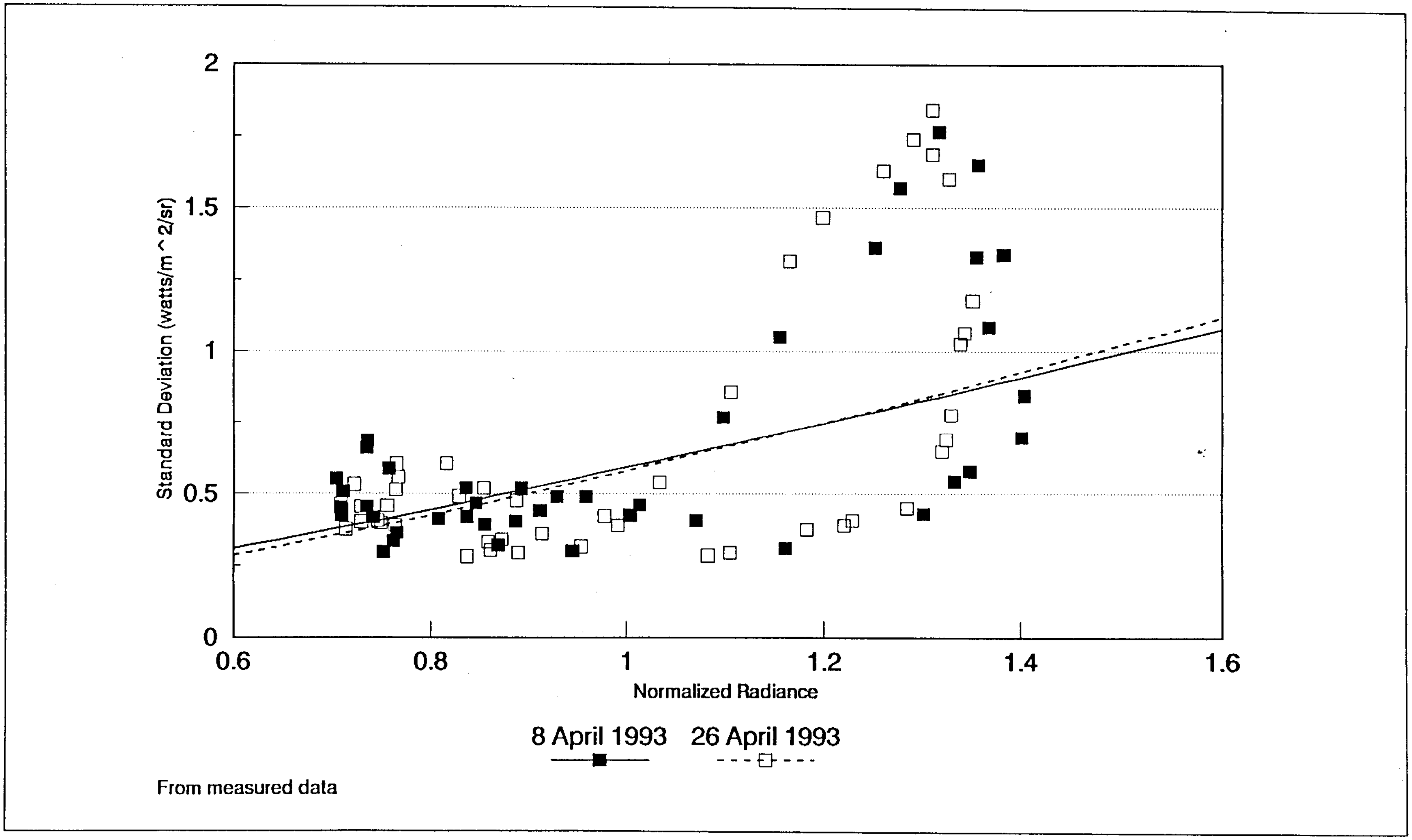

Figure 16. A comparison of the measured standard deviation of the radiance and the normalized measured radiance for desert pavement at Yuma, AZ, on 8 April and 26 April 1993. The solid and dotted lines are best fit power law fits to the data and are presented to show the inadequacy of this description of the full 24-hr diurnal variation

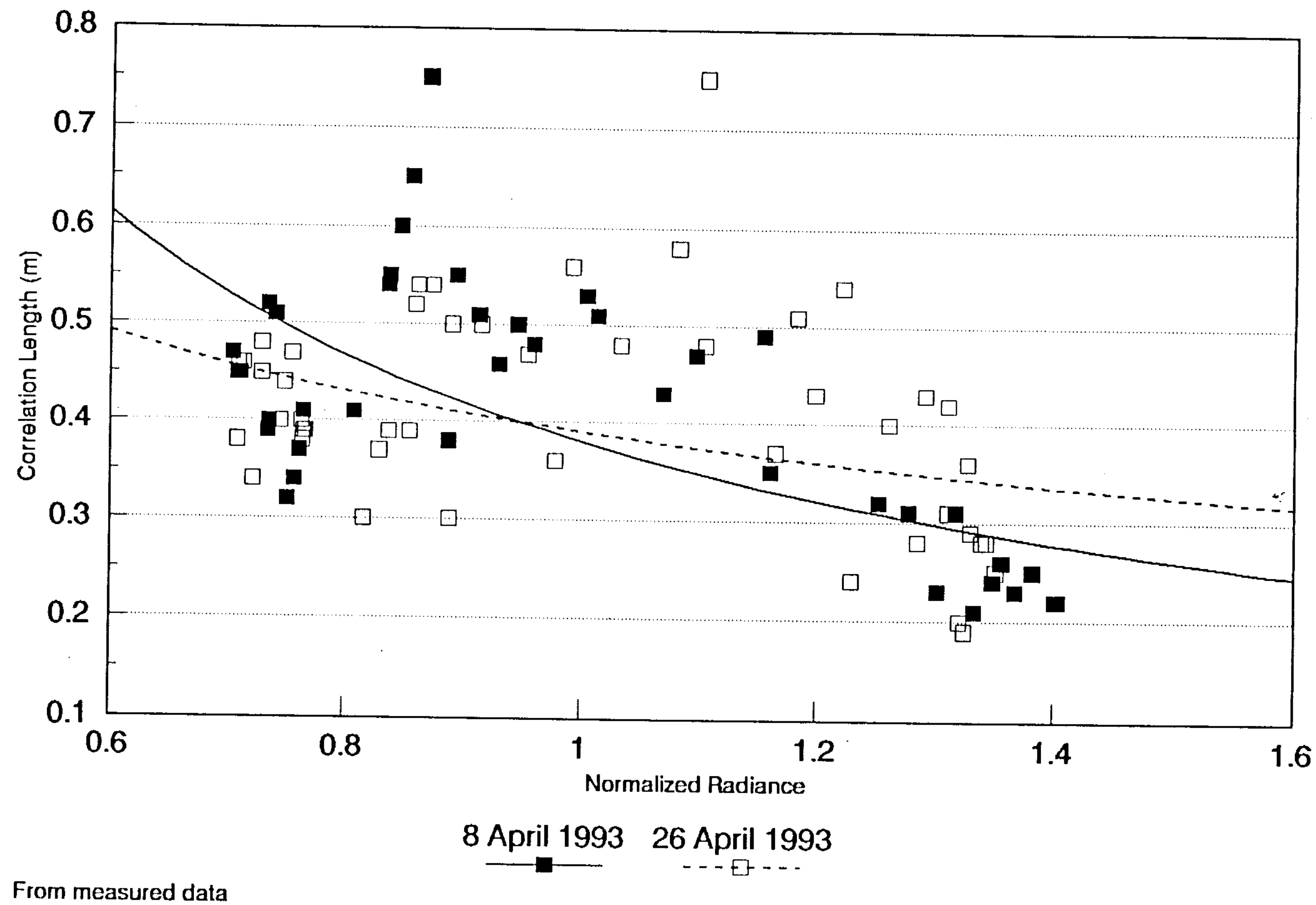

Figure 17. A display of the measured correlation length of the radiance versus the normalized values of the measured radiance for desert pavement at Yuma, AZ, on 8 April and 26 April 1993. The solid and dotted lines are best fit power laws and are not adequate to fit the 24-hr diurnal variation

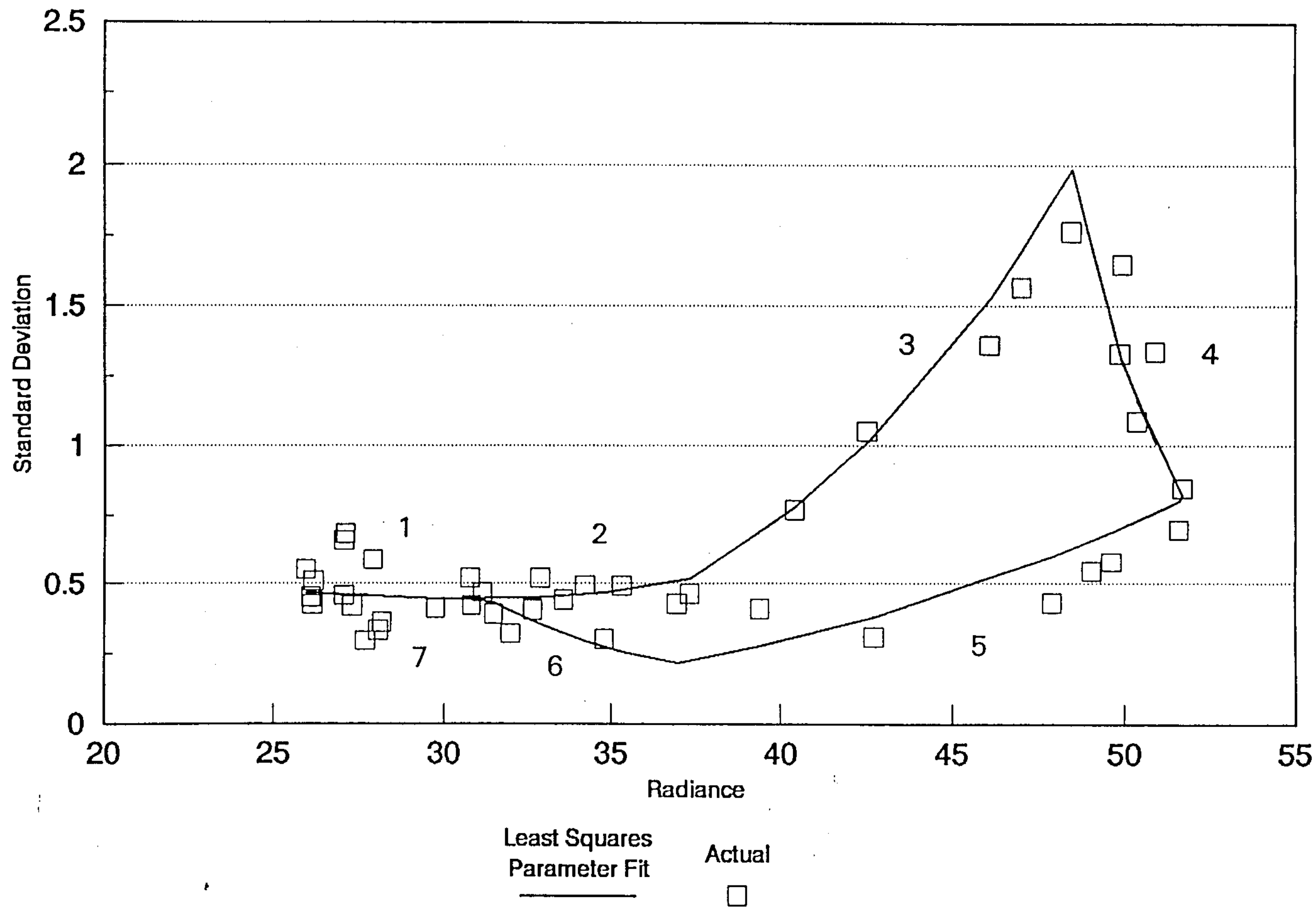

Figure 18. A 2-day least squares parameter fit using a power law for the standard deviation of the radiance versus the radiance in seven radiance bands is compared with the measured data from 8 April 1993 at Yuma, AZ

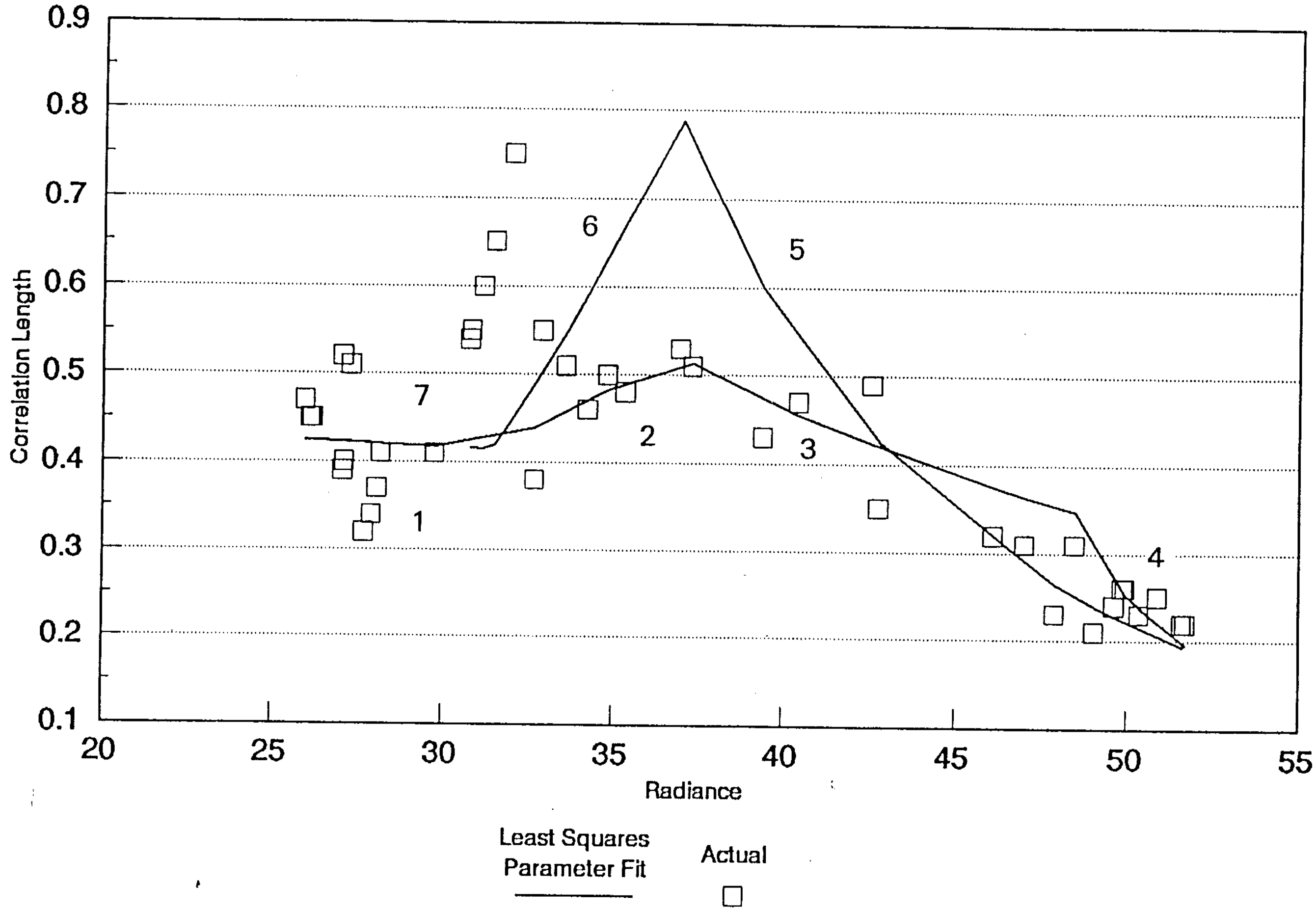

Figure 19. The 2-day least squares parameter fit using a power law of the correlation length of the radiance versus the radiance over seven radiance bands is compared with the measured data for 8 April 1993 at Yuma, AZ

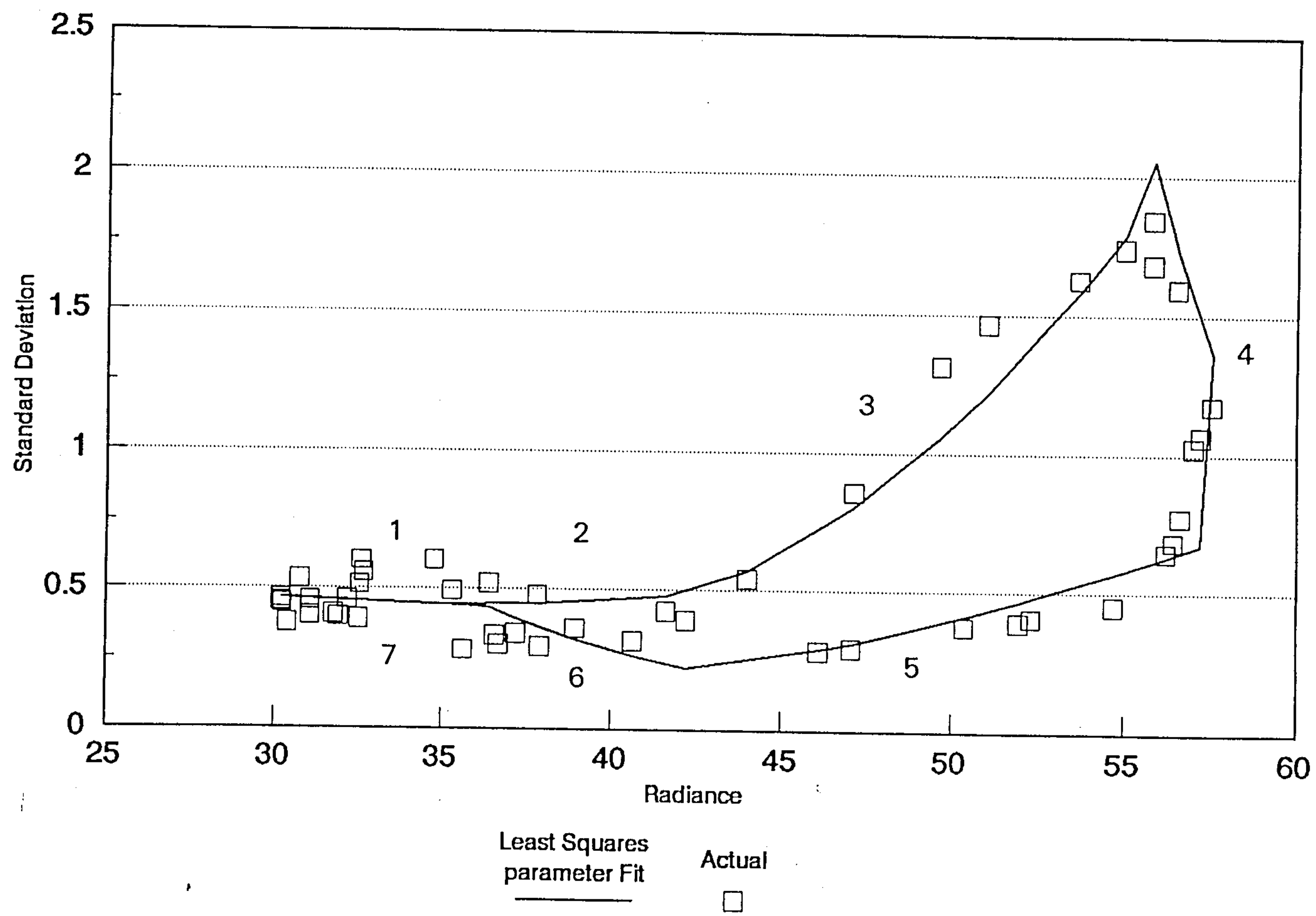

Figure 20. A 2-day least squares parameter fit using a power law to represent the standard deviation of the radiance versus the radiance in each of the seven radiance bands is compared with the measured data for 26 April 1993 at Yuma, AZ

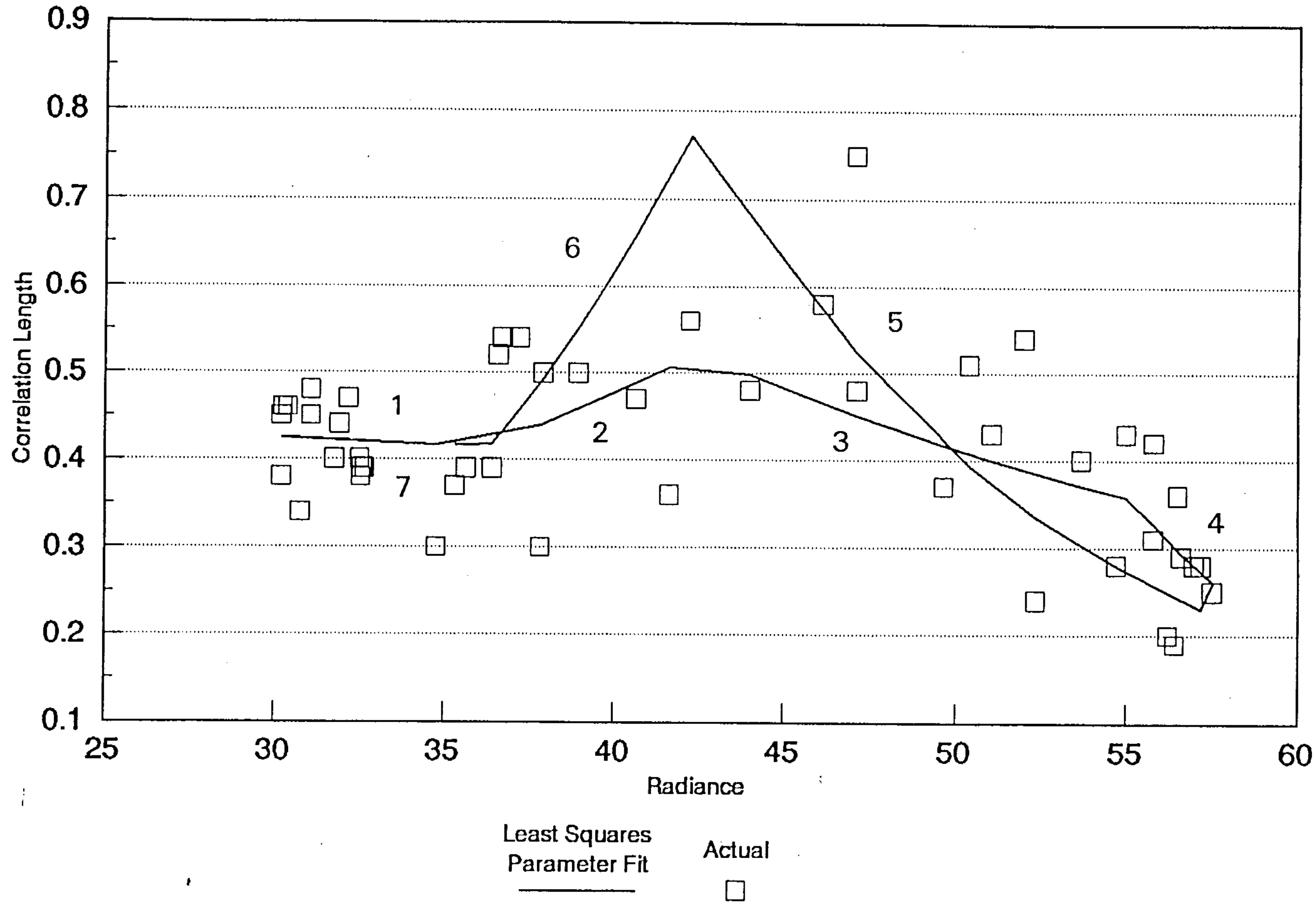

Figure 21. The 2-day least squares parameter fit using a power law to represent the correlation length of the radiance versus the radiance in seven radiance bands is compared with the measured data for 26 April 1993 at Yuma, AZ

the standard deviation and correlation length of the radiance versus the average radiance for the power laws given by Equations 103 and 104. In this way, the coefficients b, δ, c, and β are determined. The power law representations of the measured standard deviation and correlation length of the radiance are displayed versus time in Figures 22-25 in which the solid lines refer to the least square fit that appears in Figures 18-21. Each parameter is plotted first versus radiance, since that is the domain in which the power function fit is made, and secondly the parameter is plotted versus time of day, so that the diurnal variation may be seen in the time domain. These curves were generated using the actual measured values of radiance, rather than the values of radiance predicted by WESTHERM. The model constants were determined by taking the weighted averages of the model constants for the 2 days according to the equations

$$b = \exp\left(\frac{n_1 \ln b_1 + n_2 \ln b_2}{n_1 + n_2}\right) \tag{108}$$

$$c = \exp\left(\frac{n_1 \ln c_1 + n_2 \ln c_2}{n_1 + n_2}\right) \tag{109}$$

$$\delta = \frac{n_1\delta_1 + n_2\delta_2}{n_1 + n_2} \tag{110}$$

$$\beta = \frac{n_1\beta_1 + n_2\beta_2}{n_1 + n_2} \tag{111}$$

where n_1 and n_2 represent samples sizes for the 2 days. Only the model constants for desert pavement were used in the development and verification of the model.

Data Reduction Procedure

Given a set of measured data $\{(x_i,y_i),\ 1 \leq i \leq n\}$, it is desired to find constants a and b such that if $y_i^* = ax_i^b$, then y^* will give the best approximation to y in the least squares sense. In actual practice, however, rather than fit the power curve directly, what is actually fit is the natural logarithm of the power curve: $\ln (y_i^*) = \ln (a) + b \ln (x_i)$. If $X_i = \ln (x_i)$, $Y_i = \ln (y_i)$, and $Y_i^* = \ln (y_i^*)$, then this equation becomes $Y_i^* = A + BX_i$, where $A = \ln (a)$ and $B = b$. The values of A and B can be found as the constants of the ordinary regression line for the measured values of (X_i,Y_i). Then $a = \exp (A)$ and $b = B$.

The diurnal cycle was divided into seven segments, and model constants were determined for each of the seven segments for standard deviation and correlation length. This was accomplished using program 'fit' (a compilation

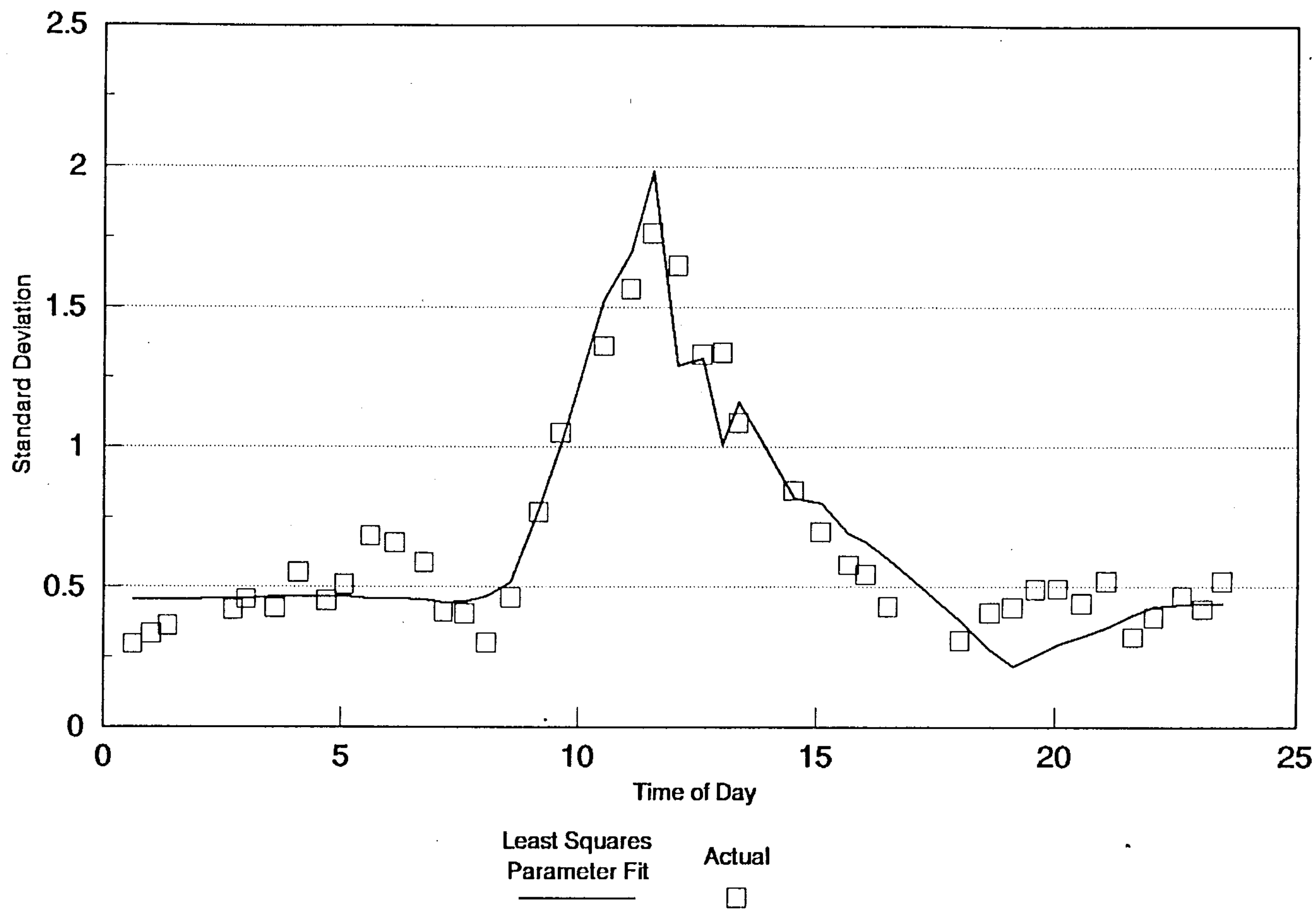

Figure 22. A comparison of the least squares fit of the standard deviation of the radiance versus radiance with measured standard deviation of the radiance expressed as a function of time for 8 April 1993 at Yuma, AZ

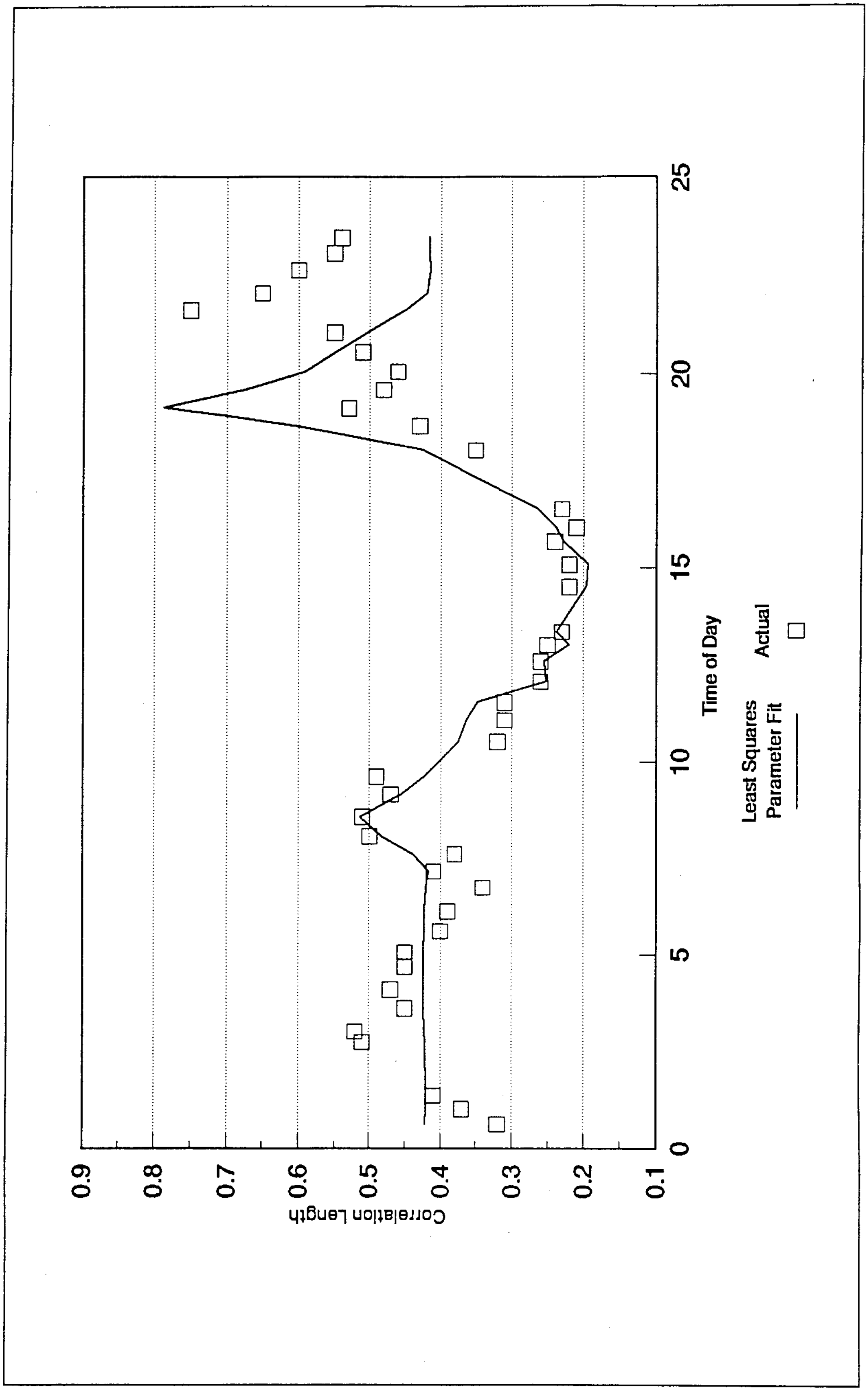

Figure 23. Comparison of the least squares fit of the correlation length of the radiance versus the radiance with the measured correlation length of the radiance expressed as a function of time for 8 April 1993

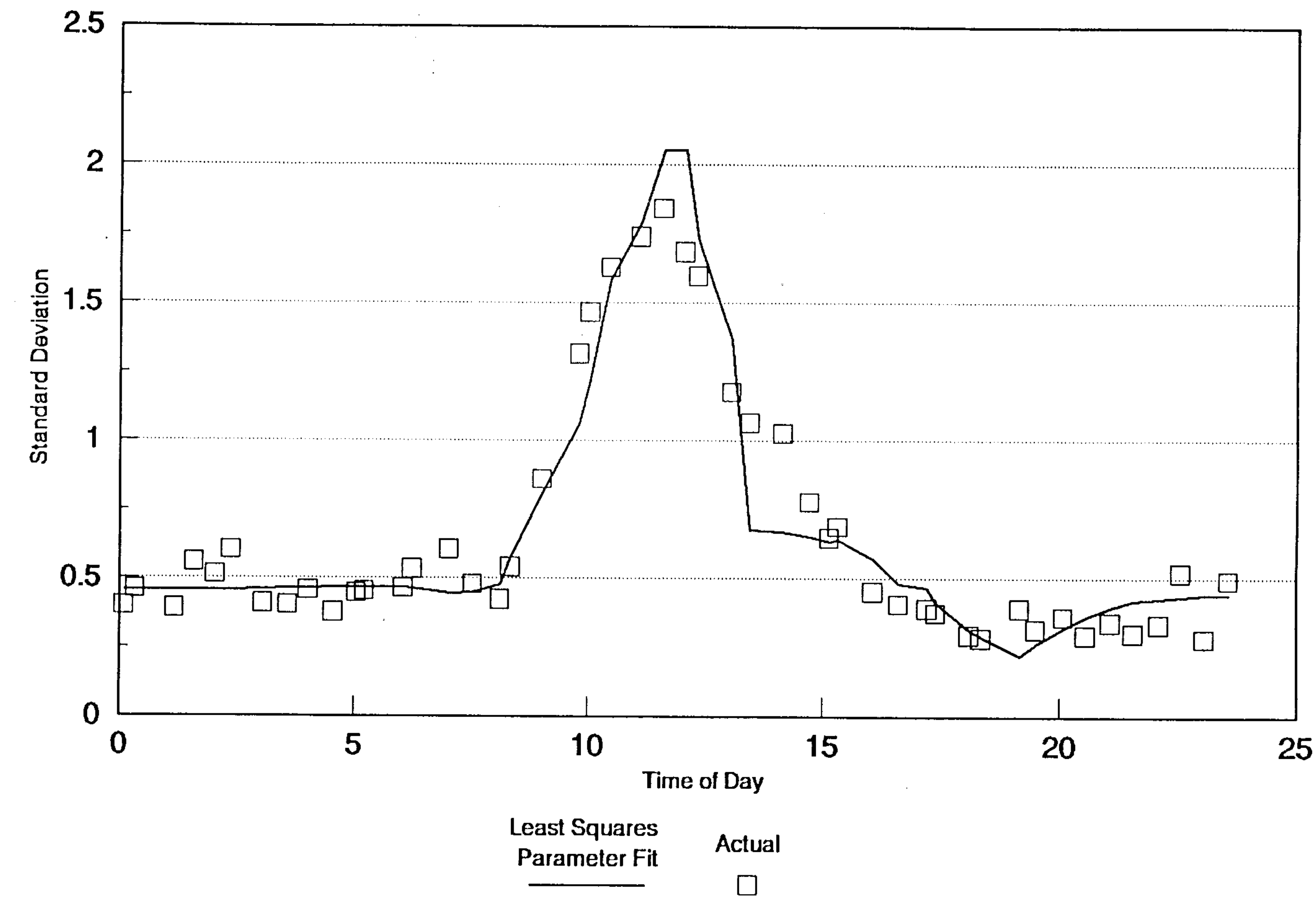

Figure 24. Comparison of the least squares fit of the standard deviation of the radiance versus radiance with the measured standard deviation of the radiance expressed in terms of time for 26 April 1993 at YUMA, AZ

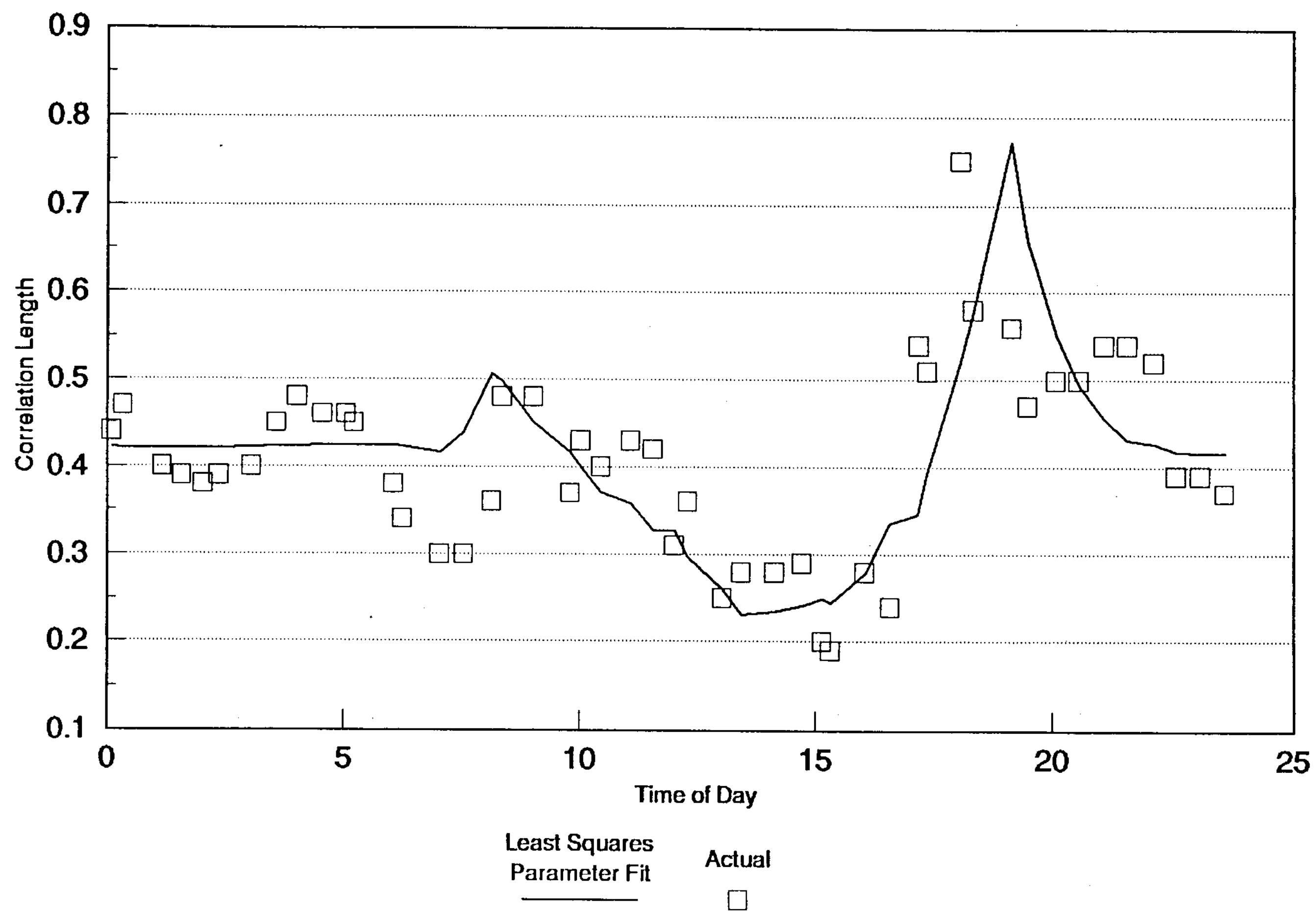

Figure 25. A comparison of the least squares fit of the correlation length of the radiance versus the radiance with the measured values of the correlation length of the radiance when expressed as function for time for 26 April 1993 at Yuma, AZ

of files fitc.c and fitf.f in Appendix A), which used data files ss040893.dat and ss042693.dat in Appendix B (Once 'fit' has been compiled, one types 'fit ss040893.dat' to run the program). The output of this program consists of data files of the type ss040893.prms and ss042693.prms in Appendix B. These files contain the model constants b,c,δ, and β, as well as information needed when averaging the two data sets. The values of κ and η are needed for making adjustments based upon camera resolution. The program 'avg' (formed by compiling files avgc.c and avgf.f listed in Appendix A) averages the data from several output files of the type ss040893.prms and ss042693.prms, and produces a file of the sort ss.avg in Appendix B. To produce an input file for 'avg' one must concatenate, into a single file, all the files with extension 'prms' which one wishes to average, taking care to remove the extra lines defining κ and η, leaving only the first two such lines. This produces a file of the type ss.all in Appendix B. One runs the compiled program by typing 'avg ss.all.' This produces the file 'ss.avg.'

The full model assumes that model constants b,c,δ, and β for each of the seven segments (called bands), are known for four different materials: bare soil, green vegetation, brown vegetation, and forest canopy. To have a full working model, one needs to have a model database of the sort represented by the file modelYDP.db in Appendix B. This is done by concatenating files such as ss.avg into a single file and removing the extra lines defining κ and η. Thus, one would need real world diurnal data of the type found in files ss040893.dat and ss042693.dat for each of these four material types. No such data are presently available. For bare soil, data from desert pavement near Yuma, AZ, was used. This material is probably at the extreme end of the range of what would be called bare soil. Since there are no data for the other three categories, model YDP.db contains zeros for the model constants in those categories. Once one has a model.db file, this serves as the input file for the program 'block' (created by compiling files blockc.c and blockf.f). Program 'block' turns the file model.db into a Fortran block data subroutine, called block.f. This routine serves as one of the modules for the texture prediction program 'texgen' (compiled from files texgen.c sdaclor.f fsdaclor.f and block.f found in Appendix A).

Selection of Diurnal Bands

Since the model predicts the values of standard deviation and correlation length in terms of the value of radiance, some method was needed to divide the diurnal cycle (which is a time cycle) according to the value of the radiance since radiance, and not time, is the independent parameter of the model. Dividing the day into bands determined by time of day produced unsatisfactory results. During a diurnal cycle, the radiance cycles through a range of values, going from a minimum value (typically around sunrise) to a maximum value during the heat of the day, then back to a lower value after sunset. The seven bands were determined according to the value of the minimum, average, and maximum radiance during a diurnal cycle. First, all radiances in the measured

data cycle are normalized by dividing by the average radiance over the cycle. Let us denote the minimum and maximum normalized radiances by n_{min} and n_{max}, respectively. In addition to these values, arbitrary values s and t are selected and adjusted empirically. Experimentation showed that values of s = 0.5 and t = 0.84 produced good results. In general, s and t must satisfy $0 < s < 1$ and $0 < t < 1$. The values of s and t are used to determine two more boundaries on the normalized radiance axis, n_s and n_t, with $n_s = (1 - s)n_{min} + s$ and $n_t = (1 - t) + tn_{max}$. Thus s is the proportionate distance of n_s between n_{min} and 1, while t is the proportionate distance of n_t between 1 and n_{max}. Over any diurnal cycle, it is always true that $n_{min} < n_s < 1 < n_t < n_{max}$. Next, the day is divided into two time zones: Zone 1 is that period of the day before the maximum radiance is attained, and zone 2 is the period after the maximum radiance is attained. A given data point falls into one of the seven bands according to the following rules based upon the measured value n of the normalized radiance:

Band 1: zone 1, and $n < n_s$
Band 2: zone 1, and $n_s \leq n < 1$
Band 3: zone 1, and $1 \leq n < n_t$
Band 4: zone 1, and $n_t \leq n \leq n_{max}$
Band 5: zone 2, and $1 \leq n < n_{max}$
Band 6: zone 2, and $n_s \leq n < 1$
Band 7: zone 2, and $n < n_s$

These bands are shown in Figures 18-21. Notice that bands 1 and 7 are actually merged into a single band. Data points lying in bands 1 and 7 are merged together by the 'fit' routine to find common model constants for both bands. Bands 2, 4, and 6 are transition bands whose constants are computed in such a way as to avoid functional discontinuities in the model. So, in practice, only data points in bands 1, 3, 5, and 7 are actually needed to determine the model constants for all seven bands. Model constants for bands 2, 4, and 6 are computed from the model constants of bands 1, 3, 5, and 7 by the 'fit' routine. However, the model constants for these transition bands are recomputed at run-time since they depend upon the actual radiances predicted by WESTHERM. The equations used to compute the model constants in bands 2, 4, and 6 are presented below.

Computation of Model Constants for Bands 2, 4, and 6

For the models at hand, the task is to define two functions that are piecewise power functions on an interval $[n_{min}, n_{max}]$, where $n_{min} < n_s < 1 < n_t < n_{max}$. The two power functions, $P_1(n)$ and $P_2(n)$, are defined as follows:

$$P_1(n) = \left\{ \begin{array}{l} a_1 n^{b_1} \; for \; n_{\min} \le n < n_s \\ a_2 n^{b_2} \; for \; n_s \le n < 1 \\ a_3 n^{b_3} \; for \; 1 \le n < n_t \\ a_4 n^{b_4} \; for \; n_t \le n \le n_{\max} \end{array} \right\} \qquad (112)$$

$$P_2(n) = \left\{ \begin{array}{l} a_7 n^{b_7} \; for \; n_{\min} \le n < n_s \\ a_6 n^{b_6} \; for \; n_s \le n < 1 \\ a_5 n^{b_5} \; for \; 1 \le n \le n_{\max} \end{array} \right\} \qquad (113)$$

where, for some s and t satisfying $0 < s < 1$ and $0 < t < 1$,

$$n_s = (1-s) n_{\min} + s\,1 \qquad (114)$$

and

$$n_t = (1-t)\,1 + t n_{\max} \qquad (115)$$

By the nature of the application, the values of a_1, a_3, a_5, a_7, b_1, b_3, b_5, and b_7 are given. It is also given that $a_1 = a_7$, and $b_1 = b_7$. The problem is to determine the values of a_2, a_4, a_6, b_2, b_4, and b_6 which will make $P_1(n)$ and $P_2(n)$ continuous on the interval $[r_{min}, r_{max}]$, and which will make $P_1(n_{max}) = P_2(n_{max})$. In order for these conditions to be satisfied, the following equations must hold:

$$a_1 n_s^{b_1} = a_2 n_s^{b_2} \qquad (116)$$

$$a_2 1^{b_2} = a_3 1^{b_3} \qquad (117)$$

$$a_3 n_t^{b_3} = a_4 n_t^{b_4} \qquad (118)$$

$$a_4 n_{max}^{b_4} = a_5 n_{max}^{b_5} \tag{119}$$

$$a_5 1^{b_5} = a_6 1^{b_6} \tag{120}$$

$$a_7 n_s^{b_7} = a_1 n_s^{b_1} = a_6 n_s^{b_6} \tag{121}$$

From Equations 117 and 120 it follows that $a_2 = a_3$, and $a_6 = a_5$, independently of the values of s, t, n_{min}, and n_{max}. From Equations 116 and 117, we conclude that

$$b_2 = b_1 + \frac{\ln a_1 - \ln a_3}{\ln n_s} \tag{122}$$

From Equations 118 and 119 we conclude that

$$b_4 = \frac{\ln\left(\dfrac{a_3 n_t^{b_3}}{a_5 n_{max}^{b_5}}\right)}{\ln\left(\dfrac{n_t}{n_{max}}\right)} \tag{123}$$

and

$$a_4 = a_5 n_{max}^{b_5 - b_4} \tag{124}$$

From Equations 121 we conclude that

$$b_6 = b_1 + \frac{\ln a_1 - \ln a_5}{\ln n_s} \tag{125}$$

Model Validation

After deriving model constants for standard deviation and correlation length for the seven bands, based upon the Yuma desert pavement data, it was possible to attempt a verification of the model. In the spring of 1994, data were collected at Grayling, MI (Rivera 1994b). This was not diurnal data, so a full validation could not be conducted. IR images from several days were analyzed in order to determine radiance, standard deviation of radiance, and correlation length of radiance from a patch of sandy road. While there was no

reason to expect that the model parameters for desert pavement at Yuma, AZ, would be identical to model parameters for a sandy test track at Grayling, MI, it was felt that they should be sufficiently similar and that the predicted diurnal variation would produce curves of the expected shape, perhaps being off by some constant multiple. This is, in fact, what was found. Only three or four data points were available for each day for which data were available. Figures 26-33 show a comparison of the predicted and measured radiances and brightness temperatures for 3 days of measurements at the Grayling test site. Actual model constants for the Grayling site are unknown because diurnal radiance measurements were not acquired. In modifying the Yuma model constants, only the values of b and c were changed. The values of the exponents β and δ were unchanged. The altered model constants are found in the file 'modelGTT.db' in Appendix B. Brightness temperature, T_B, and standard deviation of brightness temperature, σ_{TB}, were computed from radiance, N, and standard deviation of radiance, σ_N, using the following approximations on the 8- to 12-µm range:

$$T_B = \frac{1332.5}{\ln\left[1 + \frac{3305.8}{N}\right]} \tag{126}$$

$$\sigma_{TB} = 2.27 \ X \ 10^{-7} T_B^2 \ [\exp\left(\frac{1332.5}{T_B}\right) - 1]\sigma_N \tag{127}$$

which are obtained from Equations 78 and 88. Results were converted to Celcius using the relation

$$t_b = T_B - 273.15 \tag{128}$$

$$\sigma_{tb} = \sigma_{TB} \tag{129}$$

where t_b and σ_{tb} are the average and standard deviations of the brightness temperature measured in degrees Celsius.

Use of WESTEX Program

In its present form, the model can be used to predict diurnal variation in standard deviation of radiance and correlation length of radiance for either desert pavement at Yuma, AZ, or sandy test track at Grayling, MI, for any date for which a met file exists. The met file is a prerequisite for running WESTHERM, from which the diurnal radiance is predicted. The TEXGEN program is produced by compiling the files 'texgen.c', 'sdaclor.f', 'fsdaclor.f', together with one of the bdata.f files, either 'bdataYDP.f' or 'bdataGTT.f'.

The program is designed to be run in a Unix environment with command line parameters. One may type 'texgen' to get a list of the required parameters. They are, in order: (a) xv, the percent of vegetation versus bare soil in the surface material, (b) xlv, the percent of the vegetation that is green, (c) resolution, the camera resolution in pixels per meter, and (d) infile, the name of the output file from WESTHERM containing the diurnal radiance profile (such as the file 08994.bare in Appendix B); outfile, the name of the file you wish the output of texgen to go to.

Since there are presently no model constants available for green vegetation, brown vegetation, or forest canopy, xv and xlv should be set to 0.0. Actually, the model can be run in this mode on any material by substituting the model parameters for Yuma desert pavement with the model parameters for the material in question. In order to determine those model parameters, it is necessary to have diurnal information about the material in the format found in, for example, the file ss040893.dat in Appendix A. If the information is available and cannot conveniently be put into that format, then the 'fetch' subroutine of the 'fitf.f' module will have to be rewritten to accommodate the different format. (This is a trivial exercise for a programmer.) Running 'fit' on the data will produce a file that can be manipulated according to the procedure outlined in part 5, Data Reduction Procedure, to produce an appropriate bdata.f file. If this procedure is used to find model parameters for green vegetation, brown vegetation, and forest canopy, then the model parameters may be cut and pasted into the model.db file to produce a complete bdata.f module.

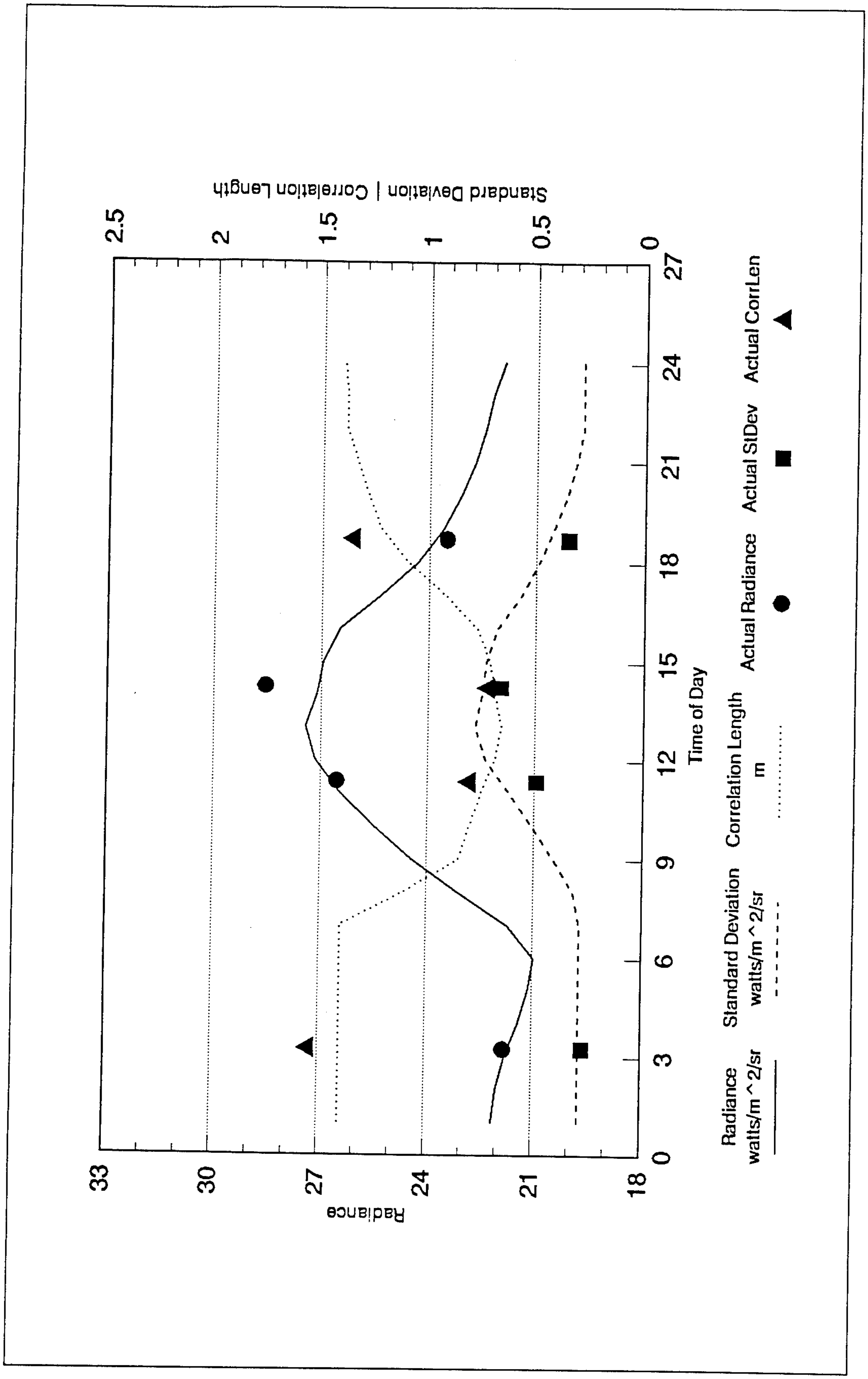

Figure 26. Theoretical prediction of the time dependence of the radiance, standard deviation of the radiance, and the correlation length of the radiance compared with the corresponding measured values of these quantities at Grayling, MI, on 30 March 1994

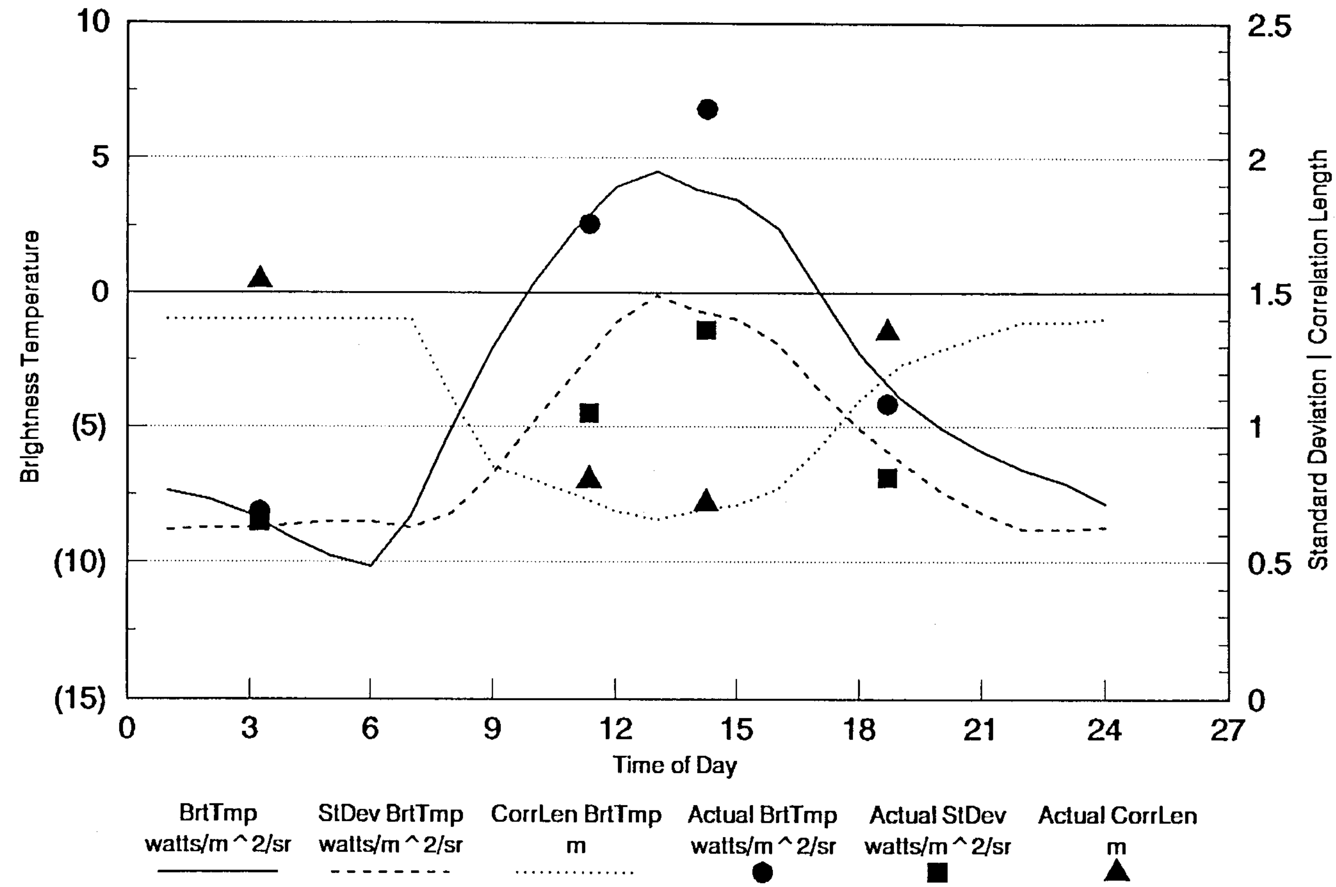

Figure 27. Theoretical prediction of the time dependence of the brightness temperature, standard deviation of the brightness temperature, and the correlation length of the brightness temperature compared with the corresponding measured values of these quantities at Grayling, MI, on 30 March 1994

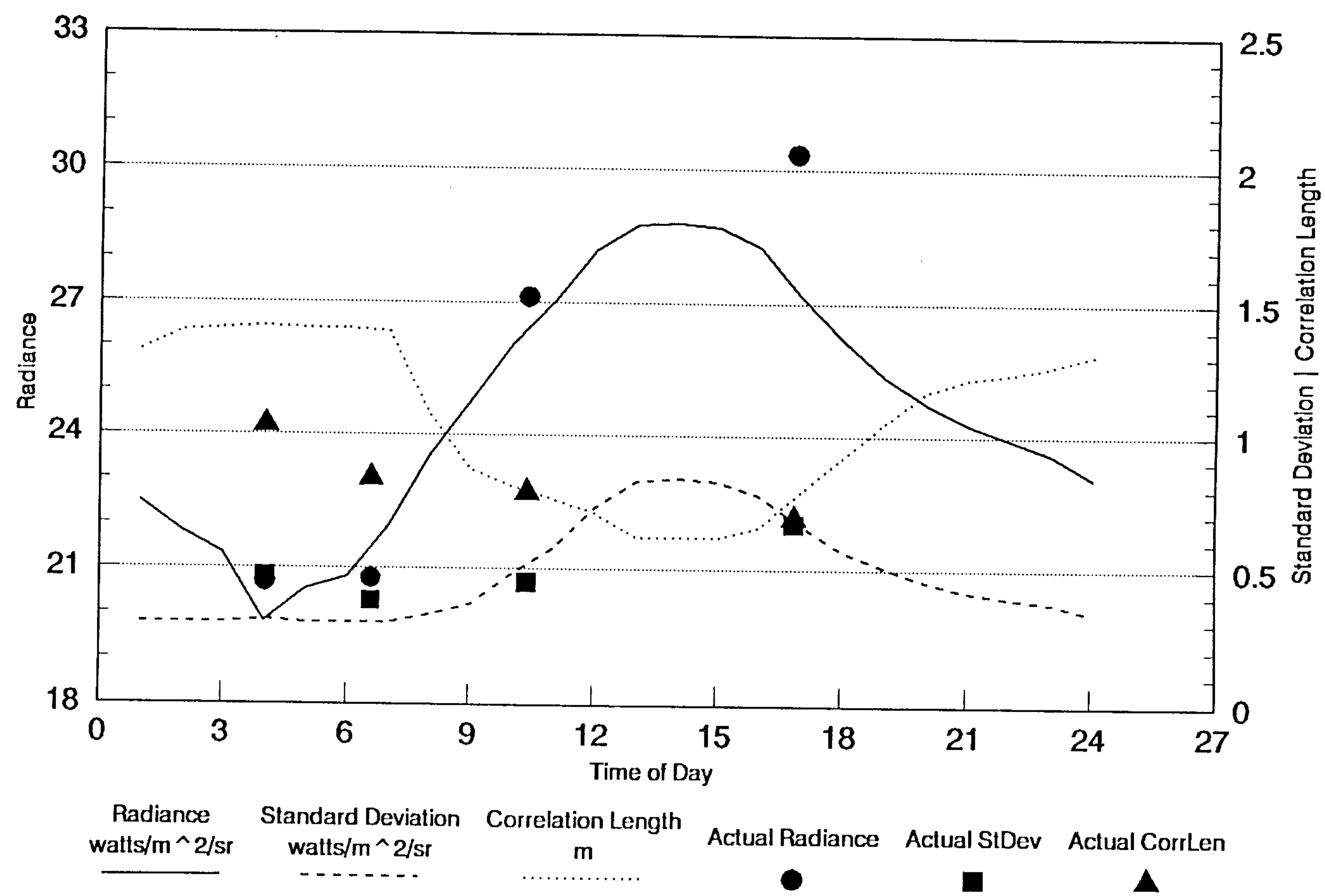

Figure 28. Theoretical prediction of the diurnal variation of the radiance, standard deviation of the radiance, and the correlation length of the radiance compared with the measured values of these quantities at Grayling, MI, on 31 March 1994

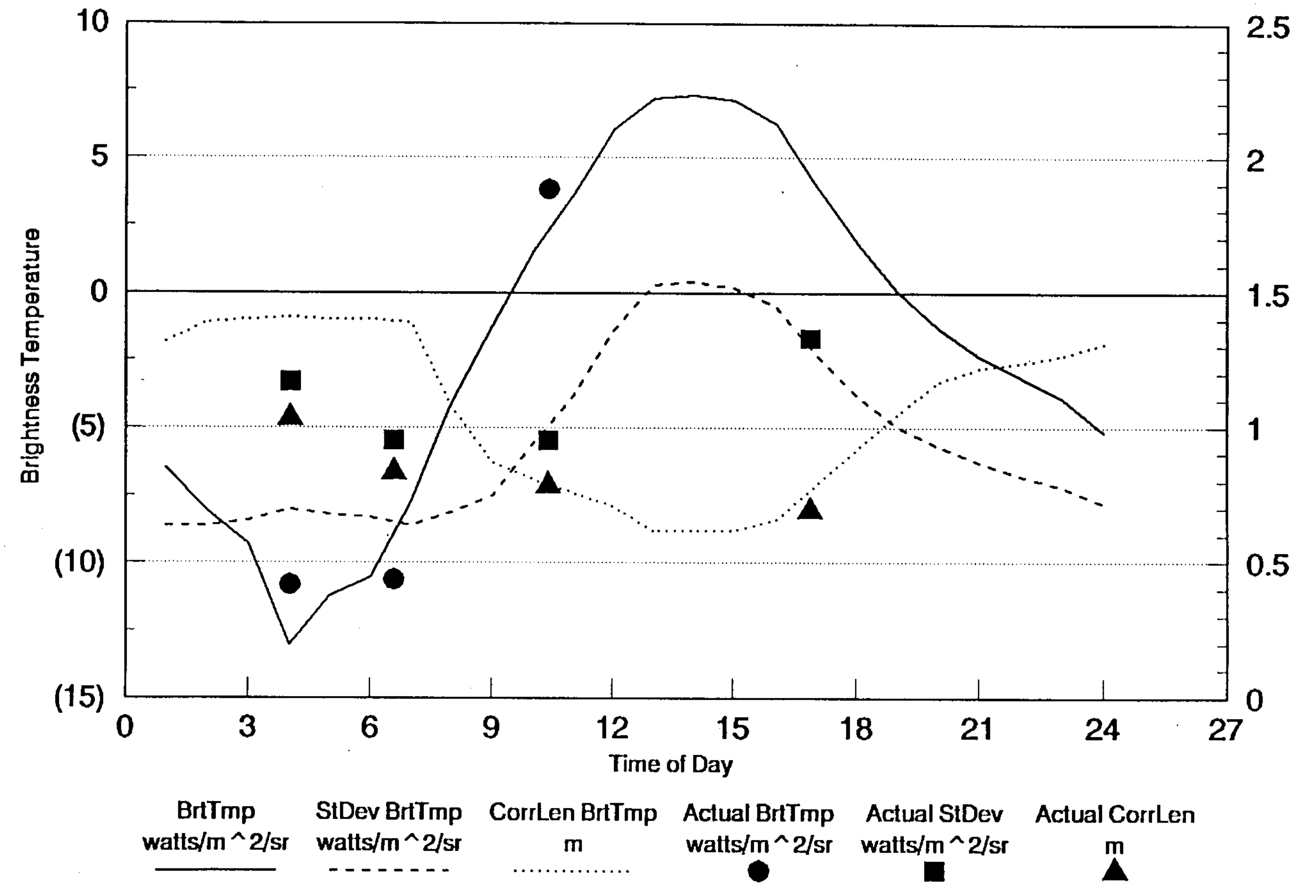

Figure 29. Theoretical prediction of the diurnal variation of the brightness temperature, standard deviation fo the brightness temperature, and the correlation length of the brightness temperature compared with the corresponding measured values of these quantities at Grayling, MI, 31 March 1994

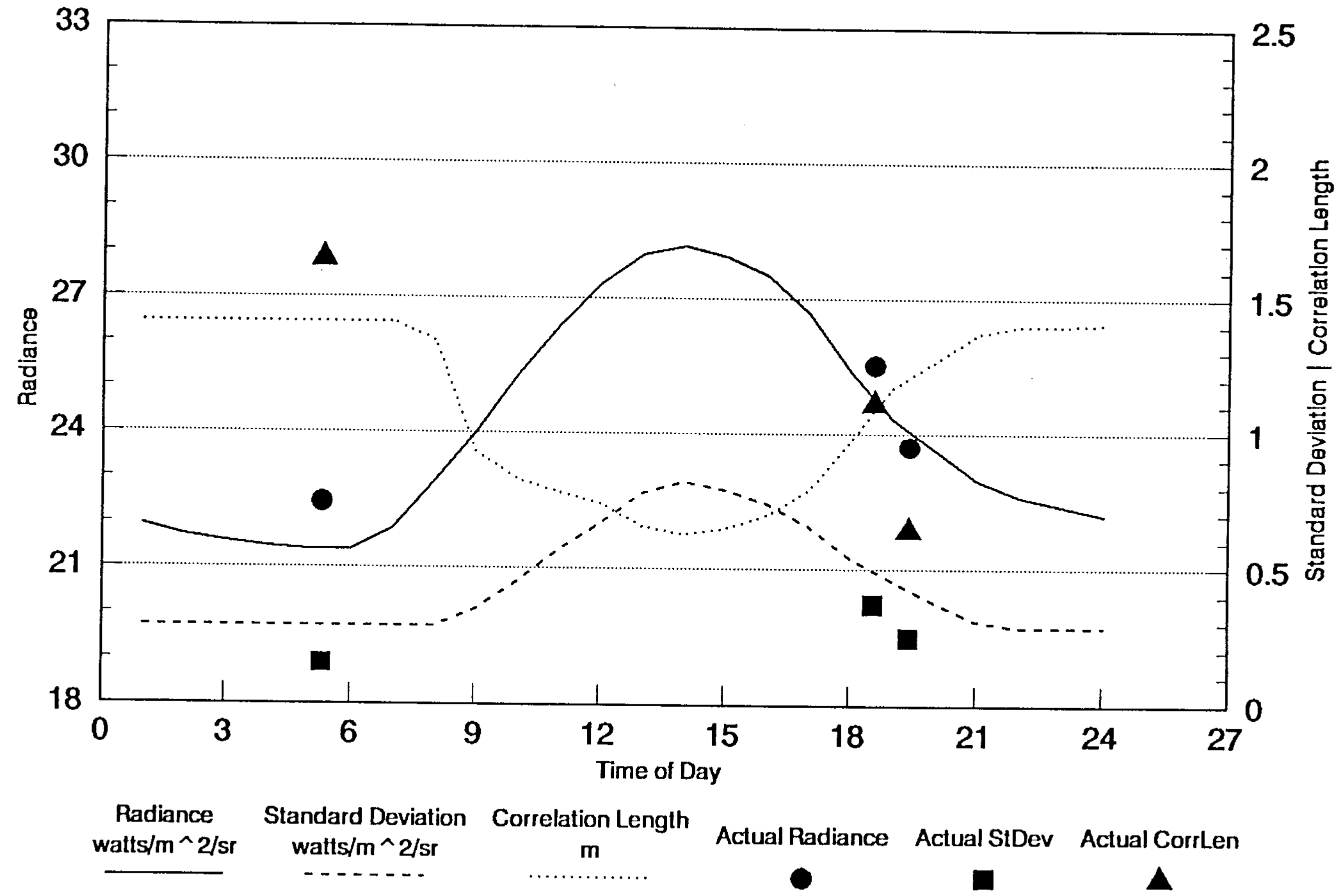

Figure 30. Theoretical prediction of the time variation of the radiance, standard deviation of the radiance, and the correlation length of the radiance compared with the measured values of these quantities for Grayling, MI, on 3 April 1994

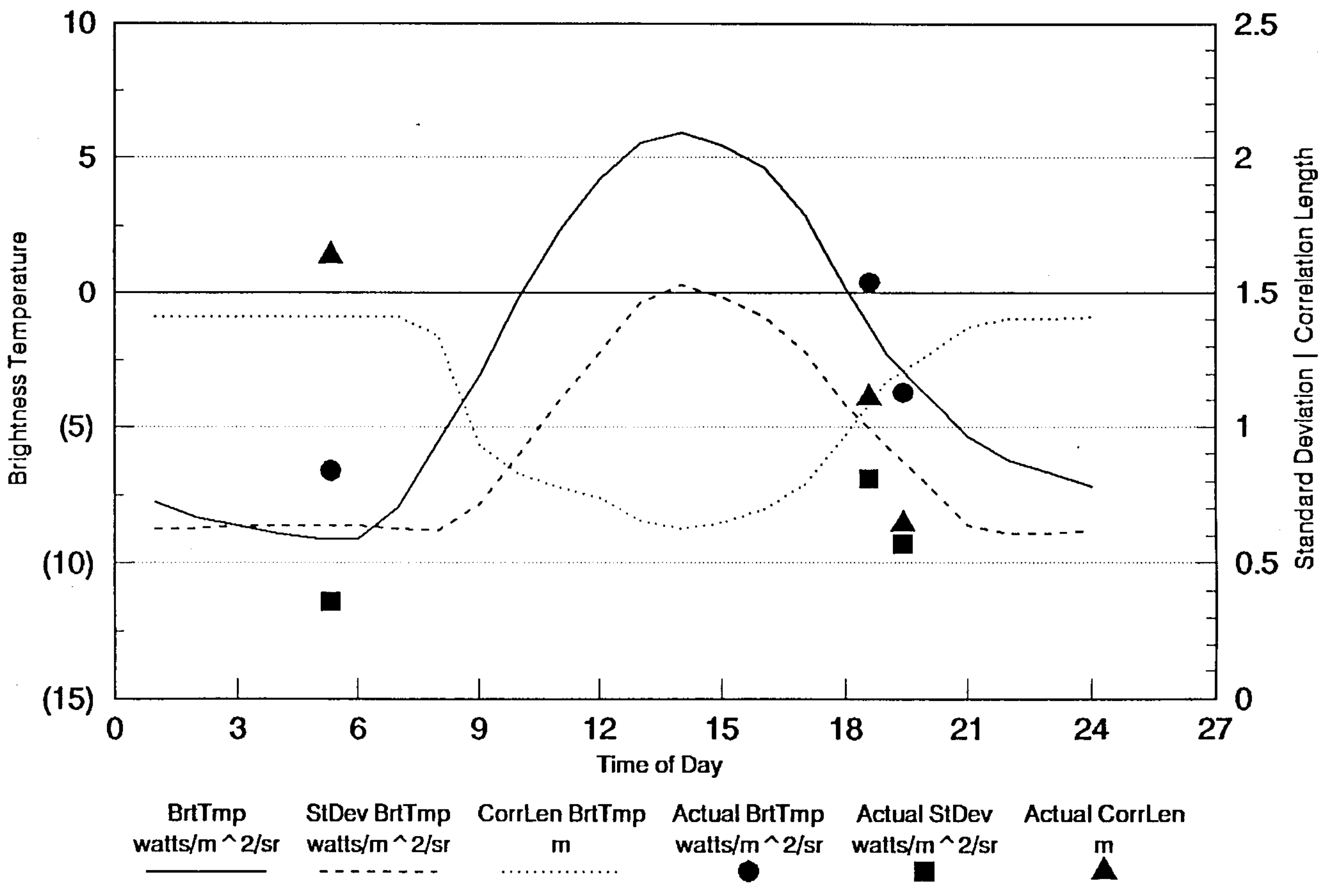

Figure 31. Theoretical prediction of the time variation of the brightness temperature, standard deviation of the brightness temperature, and the correlation length of the brightness temperature compared with the measured values of these quantities for Grayling, MI, on 3 April 1994

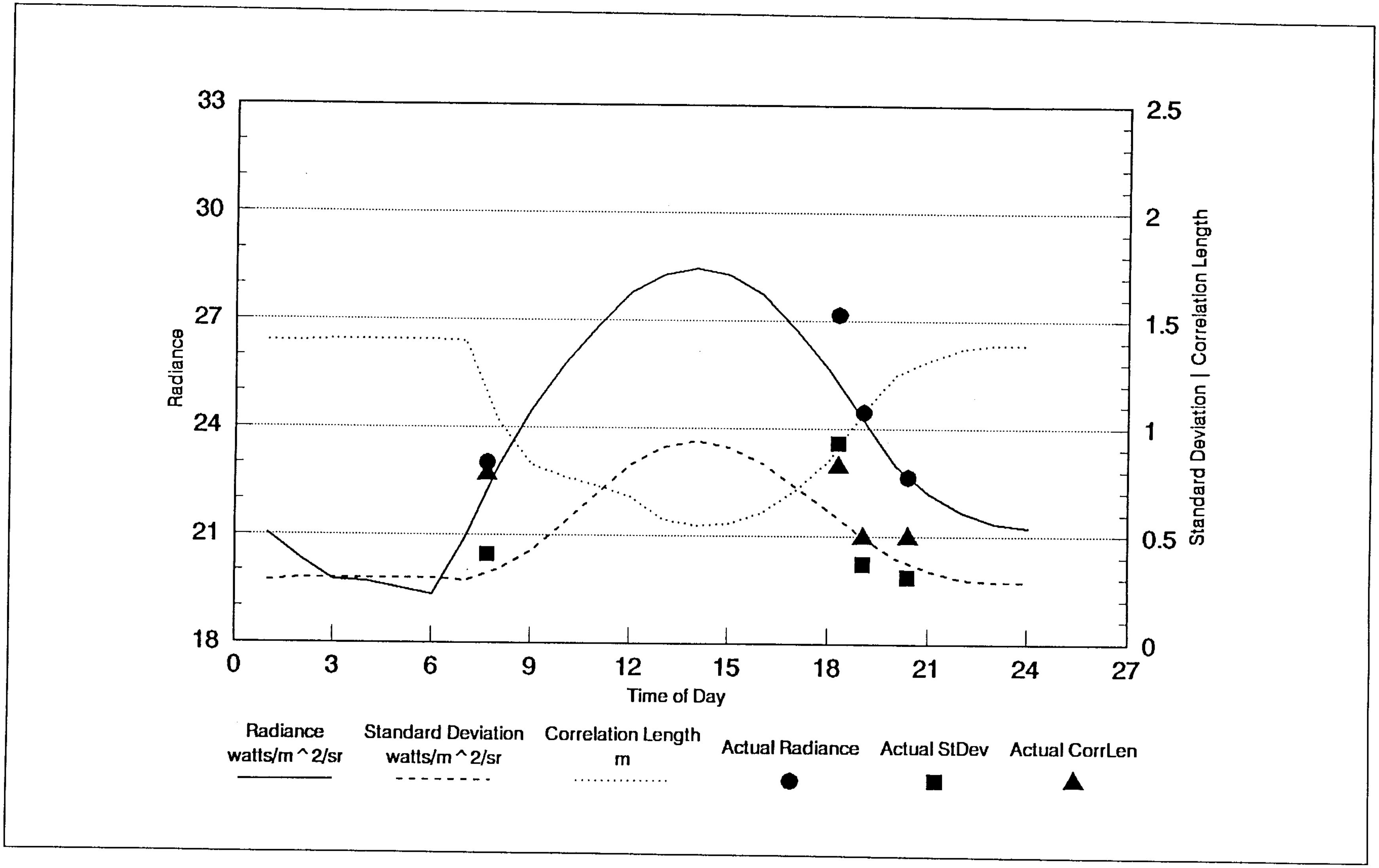

Figure 32. Theoretical prediction of the time dependence of the radiance, standard deviation of the radiance, and the correlation length of the radiance compared with the measured values of these quantities for Grayling, MI, on 7 April 1994

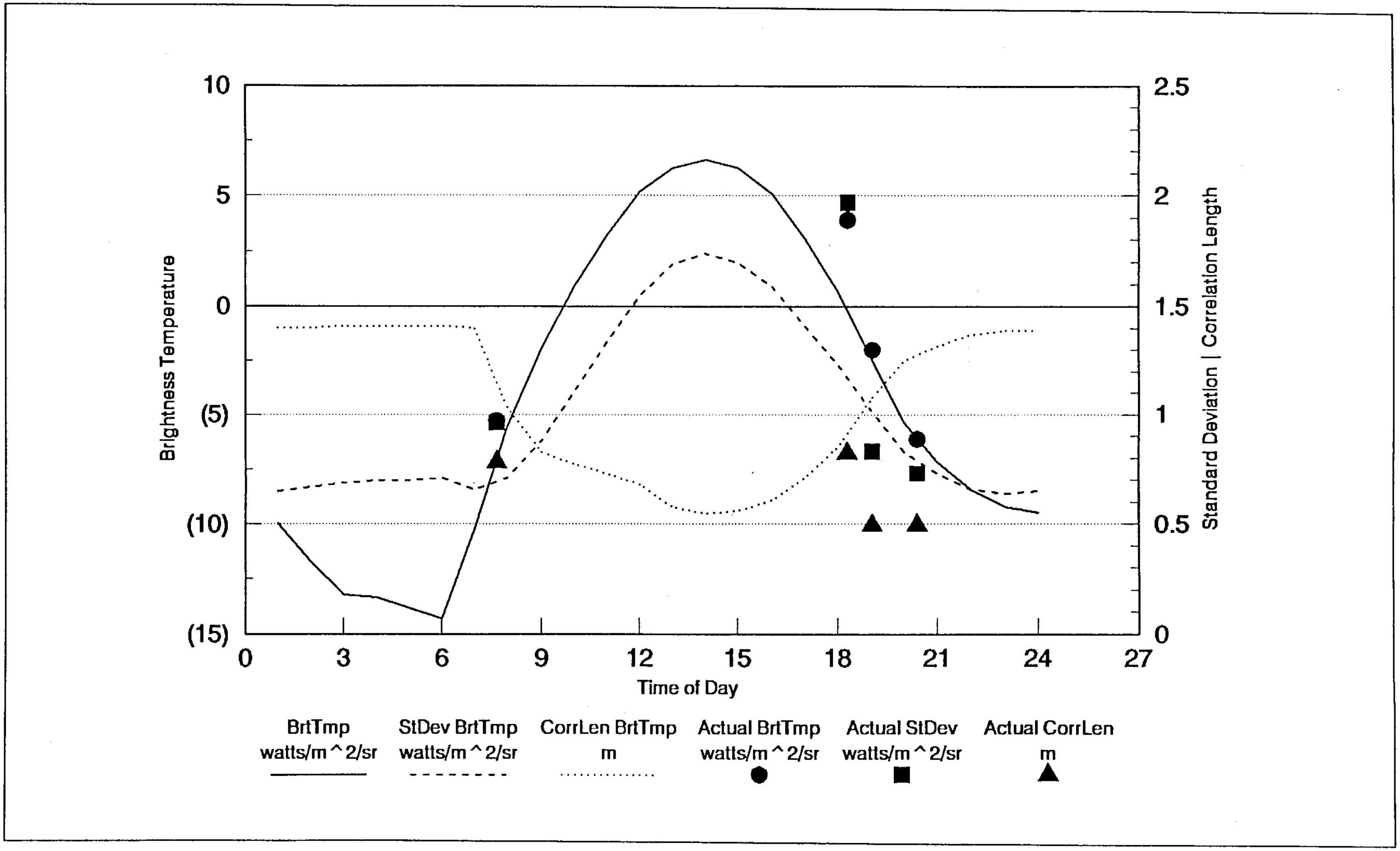

Figure 33. Theoretical prediction of the time variation of the brightness temperature, standard deviation of the brightness temperature, and the correlation length for the brightness temperature compared with the measured values of these quantities for Grayling, MI, on 7 April 1994

6 Conclusions and Recommendations

Conclusions

This report describes a physics-based terrain radiance model that predicts the standard deviation and correlation length of the IR radiance of terrain areas such as soil, grass and shrubs, and forest canopies. The predicted radiance statistics are expressed in terms of sensor characteristics such as resolution and wave band, and in terms of environmental conditions such as weather, time of day, and the physical characteristics of terrain. This simple model requires the determination of several empirical constants by fitting the model to measured IR images at several terrain sites including soil, grass, and forest canopy areas. When these constants are determined, the model will have the capability of predicting the radiance statistics for any time of day and for any terrain area where the weather conditions and terrain characteristics are specified. The terrain texture model that is described in this report can be used to generate texture for uniform areas of soil, grass, soil-grass combination, and tree canopies that often appear in synthetically generated IR scenes/images.

The study of IR terrain texture modeling produced the following conclusions:

a. A model for predicting IR terrain texture can be developed by using simple power law equations to connect the average values of the standard deviation and correlation length of the radiance in a uniform area of an IR image to the average values of the point radiance in the image. Because the average of the point radiance values is predicted by WESTHERM in terms of terrain, weather, season, and time of day, it follows that the terrain texture model can predict the standard deviation and correlation length of the radiance in terms of these environmental conditions.

b. A set of site-independent and weather-independent empirical coefficients can be determined and used to relate the standard deviation and correlation length of the radiance to the average value of the radiance

in an IR image. These coefficents are determined from measured IR images of uniform terrain areas.

c. Planck's radiation law can be used to relate the standard deviation and correlation length of the radiance to the standard deviation and correlation length of the brightness temperature, physical temperature, and terrain surface emissivity.

Recommendations

The study of the modeling of IR texture of terrain areas suggests the following recommendations:

a. Diurnal IR image data should be acquired and processed for various terrain types in addition to the desert pavement considered in this report. These terrain types include the following: bare soils; asphalt, gravel, and concrete roads; grass and tree canopies. These data should then be included in WESTEX texture prediction capability.

b. The terrain texture model that is described in this report should be used in conjunction with the ARMA texture generation algorithm to generate synthetic IR scenes/images that include a texture component. The synthetically generated scenes/images should be compared with measured images to check for realism.

c. A theoretical study should be initiated to examine the physical basis of IR texture and to use measured IR data to determine terrain parameter variability.

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Appendix A
Data Reduction Modules and WESTEX Texture Prediction Modules

Item A.1: Contents of file 'fitc.c'

```
#include <stdio.h>
#include <string.h>
main (argc,argv)
int argc;
char *argv[];
{
   if ( argc<2 ) {
      puts("usage: fit filename");
      exit(0);
   }
   fit_(argv[1]);
}
```

Item A.2: Contents of file 'fitf.f'

```
      subroutine fit(infile)

***********************************************************************
*                                                                     *
*     This program takes, as input, a file containing radiance and    *
*     standard deviation of radiance (in watts per square meter per   *
*     steradian) and correlation length (in meters) of one of the     *
*     four material types: bare soil, green short vegetation, brown   *
*     short vegetation and forest canopy.  The data must cover a      *
*     complete twenty four hour diurnal cycle with at least one data  *
*     point per hour.  The file must be arranged and formatted        *
*     to be read by the fetch routine.                                *
*                                                                     *
***********************************************************************

      real x(60),y(60),z(60),times(60),xnorm(60)
      character*13 date(60)
      character*20 feature
      character*20 infile
      real b(7),delta(7),c(7),beta(7)
      integer num(4)
      real eta,kappa
      data eta /1.0/
      data kappa /-1.0/
*
* Read in the data file.  x = radiance, y = standard deviation of
* radiance, and z = correlation length.
*
      call fetch(resolution,n,x,y,z,date,feature,infile)
*
* Normalize the data by dividing by the average radiance over
* the diurnal cycle.  xnorm = normalized radiance.
*
      call normal(n,x,xnorm)
*
* For each of the seven segments, do a least squares curve fit for
* standard deviation and correlation length in terms of normalized
* radiance according to the model y = p*x^q, where p and q are
* constants whose value is determined by the method of least squares
*
* For the first call, find b and delta such that y = b*xnorm^delta
* for each of the seven segments.
*
      call lsq(n,xnorm,y,b,delta,num)
*
* For the second call, find c and beta such that z = c*xnorm^beta
* for each of the seven segments.
*
      call lsq(n,xnorm,z,c,beta,num)
*
* Divide the b and c coefficients by the resolution factors to unbias
```

```
* the coefficients. In the model, these factors will be remultiplied
* by resolution factors appropriate to the cameras being simulated.
* The resolution factor for standard deviation is resolution^eta, and
* for correlation length, it is resolution^kappa.  The provisional
* values are eta = 1 and kappa = -1.  If later experimental evidence
* points to different values for eta and kappa, appropriate changes
* must be made in the "data" statements at the top of this subroutine.
*
      call resolve(resolution,eta,kappa,b,c)

      xavg = xnorm(n+1)
      write(*,'(a,f6.2)') "Average diurnal radiance = ",xavg
      xmax = xnorm(n+2)
      xmin = xnorm(n+3)
      rn = xmin/xavg
      rx = xmax/xavg

      call results(date,feature,rn,rx,num,b,delta,c,beta,infile
     &             ,eta,kappa)

      end ! fit

*************************************************************************
      subroutine fetch(resolution,n,x,y,z,date,feature,filename)
      real x(60),y(60),z(60)
      character*13 date(60)
      character*72 heading(4)
      character*12 filename
      character*20 feature

      open (UNIT=1,STATUS='old',FILE=filename,ERR=40)

      read (1,'(a,2f9.5)') feature,r1,r2
      resolution = 2.0/(r1 + r2)

      do loop=1,4
         read (1,'(a)') heading(loop)
      end do

      n = 1
20    read (1,'(2(a,1x),1x,f8.3,5x,2(f6.4,7x))',END=30) date(n),feature,
     &                                                  x(n),y(n),z(n)
      n = n + 1
      go to 20
30    continue
      close(1)
      n = n - 1
      return

40    write (*,'(a)') "*** FILE NOT FOUND ***"
      stop

      end ! fetch
```

```
***********************************************************************
      subroutine normal(n,x,xnorm)
      real x(60),xnorm(60)
      character*12 infile

      sumx = 0.0
      xmax = x(1)
      xmin = x(1)
      do i=1,n
         sumx = sumx + x(i)
         if ( xmax .lt. x(i) ) then
            xmax = x(i)
         end if
         if ( xmin .gt. x(i) ) then
            xmin = x(i)
         end if
      end do
      xbar = sumx/real(n)
      xnorm(n+1) = xbar
      xnorm(n+2) = xmax
      xnorm(n+3) = xmin
      do i=1,n
         xnorm(i) = x(i)/xbar
      end do
      return
      end

***********************************************************************
      subroutine resolve(resolution,eta,kappa,b,c)
      real b(7),c(7)
      real eta,kappa

      do i=1,7
         b(i) = b(i)/resolution**eta
         c(i) = c(i)/resolution**kappa
      end do

      return
      end ! resolve

***********************************************************************
      subroutine lsq(n,x,y,a,b,num)

      real x(60),y(60)
      real a(7),b(7)
      integer num(4)
      real lx,ly
      data s/0.5/
      data t/0.84/

      xbar = x(n+1)
      xmax = x(n+2)
      xmin = x(n+3)
      rx = xmax/xbar
```

```
rn = xmin/xbar
rb = 1.0 - t + t*rx
ra = (1.0 - s)*rn + s
Asumlxly = 0.0
Asumlx   = 0.0
Asumly   = 0.0
Asumlxlx = 0.0
Bsumlxly = 0.0
Bsumlx   = 0.0
Bsumly   = 0.0
Bsumlxlx = 0.0
Csumlxly = 0.0
Csumlx   = 0.0
Csumly   = 0.0
Csumlxlx = 0.0
Dsumlxly = 0.0
Dsumlx   = 0.0
Dsumly   = 0.0
Dsumlxlx = 0.0

do i=1,4
   num(i) = 0
end do

kflag = 0

do  i = 1,n

    lx = alog(x(i))
    ly = alog(y(i))

    if ( x(i) .lt. ra ) then
       Asumlxly = Asumlxly + lx*ly
       Asumlx   = Asumlx + lx
       Asumly   = Asumly + ly
       Asumlxlx = Asumlxlx + lx*lx
       num(1) = num(1) + 1
    else if ( x(i) .ge. 1.0 .and. x(i) .lt.  rb
&                .and. kflag .eq. 0 ) then
       Bsumlxly = Bsumlxly + lx*ly
       Bsumlx   = Bsumlx + lx
       Bsumly   = Bsumly + ly
       Bsumlxlx = Bsumlxlx + lx*lx
       num(2) = num(2) + 1
    else if ( x(i) .ge. rb .and. kflag .eq. 0 ) then
       Csumlxly = Csumlxly + lx*ly
       Csumlx   = Csumlx + lx
       Csumly   = Csumly + ly
       Csumlxlx = Csumlxlx + lx*lx
       num(3) = num(3) + 1
       if ( rx - x(i) .le. 0.0001) then
         kflag = 1
       end if
    else if ( x(i) .ge. 1.0 .and. kflag .eq. 1 ) then
```

```
              Dsumlxly = Dsumlxly + lx*ly
              Dsumlx   = Dsumlx + lx
              Dsumly   = Dsumly + ly
              Dsumlxlx = Dsumlxlx + lx*lx
              num(4) = num(4) + 1
           end if

      end do

      p = real(num(1))
      b(1) = (p*Asumlxly - Asumlx*Asumly)/(p*Asumlxlx - Asumlx*Asumlx)
      a(1) = exp( (Asumlxlx*Asumly-Asumlx*Asumlxly)
     &          / (p*Asumlxlx-Asumlx*Asumlx) )

      p = real(num(2))
      b(3) = (p*Bsumlxly - Bsumlx*Bsumly)/(p*Bsumlxlx - Bsumlx*Bsumlx)
      a(3) = exp( (Bsumlxlx*Bsumly-Bsumlx*Bsumlxly)
     &          / (p*Bsumlxlx-Bsumlx*Bsumlx) )

      p = real(num(3))
      b(4) = (p*Csumlxly - Csumlx*Csumly)/(p*Csumlxlx - Csumlx*Csumlx)
      a(4) = exp( (Csumlxlx*Csumly-Csumlx*Csumlxly)
     &          / (p*Csumlxlx-Csumlx*Csumlx) )

      p = real(num(4))
      b(5) = (p*Dsumlxly - Dsumlx*Dsumly)/(p*Dsumlxlx - Dsumlx*Dsumlx)
      a(5) = exp( (Dsumlxlx*Dsumly-Dsumlx*Dsumlxly)
     &          / (p*Dsumlxlx-Dsumlx*Dsumlx) )
****
* Make the correct adjustments for a(2),a(6),b(2) and b(6)
* to render the functions continuous.
****
      a(2) = a(3)
      b(2) = b(1) + ( alog(a(1)) - alog(a(3)) )/alog(ra)
      a(7) = a(1)
      b(7) = b(1)
      a(6) = a(5)
      b(6) = b(7) + ( alog(a(7)) - alog(a(5)) )/alog(ra)

      return

      end ! lsq

************************************************************************
      subroutine results(date,feature,rn,rx,num,b,delta,c,beta,infile
     &                  ,eta,kappa)
      real x(60),y(60),z(60),b(7),delta(7),c(7),beta(7)
      integer num(4)
      character*13 infile,out
      character*72 heading(2)
      real eta,kappa
      character*13 date(60)
      character*7 day
      character*20 feature
```

```
*
* Name the output file by striping the extensions off the input file
* and adding the extension ".prms"
*
      locdot = index(infile,".")
      out = infile(1:locdot-1) // ".prms"

      heading(1) = "band         b          delta     c       beta "
      heading(2) = "----   -------------    -----  -------   -----"
      day = date(1)(1:7)

      open(unit=1,file=out)
         write(1,'(a,f6.2)') "eta   = ",eta
         write(1,'(a,f6.2)') "kappa = ",kappa
         write(1,'(a,2x,a)') day,feature
         write(1,'(a,4(i3,2x))') "Bandsize 1,3,4,5: ",(num(i),i=1,4)
         write(1,'(a,f5.3)') "Minimum Radiance / Average Radiance = ",rn
         write(1,'(a,f5.3)') "Maximum Radiance / Average Radiance = ",rx
         write(1,'(a)') heading(1)
         write(1,'(a)') heading(2)
         do i=1,7
            write (1,'(i3,2x,g,2x,f7.3,2x,f8.2,2x,f7.3)') i,
     &                b(i),delta(i),c(i),beta(i)
         end do
      close (1)

      write(*,'(2a)') "Output file: ",out
      return
      end ! results
```

Item A.3: Contents of file 'avgc.c'

```
#include <stdio.h>
#include <string.h>
main (argc,argv)
int argc;
char *argv[];
{
   if ( argc<2 ) {
      puts("usage: avg filename");
      exit(0);
   }
   average_(argv[1]);
}
```

Item A.4: Contents of file 'avgf.f'

```
      subroutine average(infile)

************************************************************************
*                                                                      *
* This subroutine takes, as input, the assembled values of b, delta,   *
* c and beta from several different days, and averages the values.     *
*                                                                      *
************************************************************************

      real b(10,7),delta(10,7),c(10,7),beta(10,7)
      real rn(10),rx(10)
      integer sampsize(10,4)
      character*20 infile

      call fetch(n,b,delta,c,beta,infile,sampsize,rn,rx)
      call   ave(n,b,delta,c,beta,sampsize,rn,rx)
      call store(n,b,delta,c,beta)

      end ! main

************************************************************************
      subroutine fetch(n,b,delta,c,beta,infile,sampsize,rn,rx)
      real b(10,7),delta(10,7),c(10,7),beta(10,7)
      real eta,kappa
      integer sampsize(10,4)
      real rn(10),rx(10)
      character*7 date
      character*8 variable
      character*18 string
      character*20 material
      character*20 infile,outfile
      character*38 words
      character*48 heading(2)

      open (unit=1,file=infile,status='old',err=100)

      loc = index(infile,".")
      if (loc .ne. 0) then
         outfile = infile(1:loc-1) // ".avg"
      else
         write(*,'(a)') "***INPUT FILE MUST CONTAIN EXTENSION***"
         STOP
      end if

      open (unit=2,file=outfile)

         read (1,'(a,f6.2)') variable,eta
         write(2,'(a,f6.2)') variable,eta
         read (1,'(a,f6.2)') variable,kappa
         write(2,'(a,f6.2)') variable,kappa
```

```
        n = 1
 20     read (1,'(2a)',end=50) date,material
        read (1,'(a,4(i3,2x))') string,(sampsize(n,i),i=1,4)
        read (1,'(a,f5.3)') words,rn(n)
        read (1,'(a,f5.3)') words,rx(n)
        do i=1,2
           read(1,'(a)') heading(i)
        end do

        do i=1,7

           read (1,'(i3,2x,g,2x,f7.3,2x,f8.2,2x,f7.3)') j,b(n,i),
     &          delta(n,i),c(n,i),beta(n,i)
*          write (2,'(i3,2x,f11.8,2x,f7.3,2x,f8.2,2x,f7.3)') j,b(n,i),
*    &          delta(n,i),c(n,i),beta(n,i)

        end do
        n = n+1
        go to 20

 50     n = n-1

        close(1)

        write(2,'(2a)') "AVERAGES:  ",material

        do i=1,2
           write(2,'(a)') heading(i)
        end do

        write(*,'(2a)') "Output file: ",outfile
        return

 100    write (*,'(3a)') "File '",infile(1:length),"' not found."
        stop

        end ! fetch

***********************************************************************
        subroutine ave(n,b,delta,c,beta,sampsize,rn,rx)
*
* This subroutine averages the values of b,delta,c and beta for each
* of the seven segments over several data sets.
*
        real b(10,7),delta(10,7),c(10,7),beta(10,7)
        real rn(10),rx(10)
        integer sampsize(10,4)
        integer k(4)
        data s /0.5/
        data t /0.84/

        k(1) = 1
        k(2) = 3
        k(3) = 4
```

```
      k(4) = 5

      do j=1,4
         sum1 = 0.0
         sum2 = 0.0
         sum3 = 0.0
         sum4 = 0.0
         size = 0.0

         do i=1,n
            sizenow = real(sampsize(i,j))
            size = size + sizenow
            sum1 = sum1 + alog( b(i,k(j)) )*sizenow
            sum2 = sum2 + delta(i,k(j))*sizenow
            sum3 = sum3 + alog( c(i,k(j)) )*sizenow
            sum4 = sum4 + beta(i,k(j))*sizenow
         end do
         b(n+1,k(j))     = exp( sum1/size)
         delta(n+1,k(j)) = sum2/size
         c(n+1,k(j))     = exp( sum3/size )
         beta(n+1,k(j))  = sum4/size
      end do

      b(n+1,7) = b(n+1,1)
      delta(n+1,7) = delta(n+1,1)
      c(n+1,7) = c(n+1,1)
      beta(n+1,7) = beta(n+1,1)

      rnsum = 0.0
      rxsum = 0.0

      do i=1,n
         rnsum = rnsum + rn(i)
         rxsum = rxsum + rx(i)
      end do

      rmin = rnsum/real(n)
      rmax = rxsum/real(n)
      ra = (1.0 - s)*rmin + s
      rb = 1.0 - t + t*rmax

      call adjust(ra,rb,rmax,n,b,delta)
      call adjust(ra,rb,rmax,n,c,beta)

      return
      end ! ave

************************************************************************
      subroutine adjust(ra,rb,rmax,n,a,b)

      real a(10,7),b(10,7)

      c = 1.0/alog(ra)
```

```
      a(n+1,2) = a(n+1,3)
      a(n+1,6) = a(n+1,5)
      b(n+1,2) = b(n+1,1) + ( alog(a(n+1,1)) - alog(a(n+1,3)) )/alog(ra)
      b(n+1,6) = b(n+1,7) + ( alog(a(n+1,7)) - alog(a(n+1,5)) )/alog(ra)
*     b(n+1,4) = b(n+1,3) + ( alog(a(n+1,3)) - alog(a(n+1,4)) )/alog(rb)
*     a(n+1,4) = a(n+1,5)*rmax**( b(n+1,5) - b(n+1,4) )

      return
      end ! adjust
************************************************************************
      subroutine store(n,b,delta,c,beta)
      real b(10,7),delta(10,7),c(10,7),beta(10,7)

*     Unit 2 is opened in the 'fetch' routine

         do i=1,7
            write(2,'(i3,2x,g,2x,f7.3,2x,f8.2,2x,f7.3)') i,
     &      b(n+1,i),delta(n+1,i),c(n+1,i),beta(n+1,i)
         end do

      close(2)

      return
      end ! store
```

Item A.5: Contents of file 'blockc.c'

```
#include <stdio.h>
#include <string.h>
main (argc,argv)
int argc;
char *argv[];
{
   if ( argc<2 ) {
      puts("usage: block filename");
      exit(0);
   }
   block_(argv[1]);
}
```

Item A.6: Contents of file 'blockf.f'

```
      subroutine block(infile)

************************************************************************
*                                                                      *
* This subroutine takes as input a file containing the values of eta   *
* and kappa and the values of b, delta, c and beta for all five        *
* segments and for each of the material types: bare soil, green vege- *
* tation, brown vegetation, and forest canopy.  These values are then  *
* reorganized in the form of a FORTRAN block data module.  This module *
* is compiled with the texgen.c, sdaclor.f and fsdaclor.f modules to   *
* build the texgen module. The block data module is named "bdata.f".   *
*                                                                      *
************************************************************************

      real b(7,4),delta(7,4),c(7,4),beta(7,4)
      real eta,kappa
      character*20 infile

      call fetch(b,delta,c,beta,eta,kappa,infile)
      call makebd(b,delta,c,beta,eta,kappa)

      end

************************************************************************
      subroutine fetch(b,delta,c,beta,eta,kappa,infile)
      real b(7,4),delta(7,4),c(7,4),beta(7,4)
      real eta,kappa
      character*40 line
      character*20 stuff
      character*7 variable
      character*20 infile

      open(unit=1,file=infile,status='old',err=100)
      read(1,'(a,f6.2)') variable,eta
      read(1,'(a,f6.2)') variable,kappa
         do i=1,4
            read(1,'(a)') stuff
            read(1,'(a)') line
            read(1,'(a)') line
            do j=1,7
               read(1,'(i3,2x,g,2x,f7.3,2x,f8.2,2x,f7.3)')
     &                     k,b(j,i),delta(j,i),c(j,i),beta(j,i)
            end do
         end do
      close(1)
      return

100   write(*,'(2a)') infile," not found."
      stop

      end
```

```
******************************************************************
      subroutine makebd(b,delta,c,beta,eta,kappa)
      real b(7,4),delta(7,4),c(7,4),beta(7,4)
      real eta,kappa

      open(unit=1,file="bdata.f")
         write(1,'(6x,a)') "block data"
         write(1,'(6x,a)')
     &"common /values/ b(7,9,4),c(7,9,4),delta(7,4),beta(7,4),eta,kappa"
       write(1,'(6x,a)')"real eta,kappa"
       write(1,'(6x,a)')"data b"
       write(1,'(5x,a,6(f9.5,a))')"&/",b(1,1),",",b(2,1),",",b(3,1),","
     &                                ,b(4,1),",",b(5,1),",",b(6,1),","
       write(1,'(5x,a,f9.5,a,a)')"&",b(7,1),",","56*0.0,"
       write(1,'(5x,a,6(f9.5,a))')"&",b(1,2),",",b(2,2),",",b(3,2),","
     &                                ,b(4,2),",",b(5,2),",",b(6,2),","
       write(1,'(5x,a,f9.5,a,a)')"&",b(7,2),",","56*0.0,"
       write(1,'(5x,a,6(f9.5,a))')"&",b(1,3),",",b(2,3),",",b(3,3),","
     &                                ,b(4,3),",",b(5,3),",",b(6,3),","
       write(1,'(5x,a,f9.5,a,a)')"&",b(7,3),",","56*0.0,"
       write(1,'(5x,a,6(f9.5,a))')"&",b(1,4),",",b(2,4),",",b(3,4),","
     &                                ,b(4,4),",",b(5,4),",",b(6,4),","
       write(1,'(5x,a,f9.5,a,a)')"&",b(7,4),",","56*0.0/"
       write(1,'(6x,a)')"data c"
       write(1,'(5x,a,6(f9.5,a))')"&/",c(1,1),",",c(2,1),",",c(3,1),","
     &                                ,c(4,1),",",c(5,1),",",c(6,1),","
       write(1,'(5x,a,f9.5,a,a)')"&",c(7,1),",","56*0.0,"
       write(1,'(5x,a,6(f9.5,a))')"&",c(1,2),",",c(2,2),",",c(3,2),","
     &                                ,c(4,2),",",c(5,2),",",c(6,2),","
       write(1,'(5x,a,f9.5,a,a)')"&",c(7,2),",","56*0.0,"
       write(1,'(5x,a,6(f9.5,a))')"&",c(1,3),",",c(2,3),",",c(3,3),","
     &                                ,c(4,3),",",c(5,3),",",c(6,3),","
       write(1,'(5x,a,f9.5,a,a)')"&",c(7,3),",","56*0.0,"
       write(1,'(5x,a,6(f9.5,a))')"&",c(1,4),",",c(2,4),",",c(3,4),","
     &                                ,c(4,4),",",c(5,4),",",c(6,4),","
       write(1,'(5x,a,f9.5,a,a)')"&",c(7,4),",","56*0.0/"
       write(1,'(6x,a)')"data delta"
       write(1,'(5x,a,7(f8.3,a))') "& /",delta(1,1),",",delta(2,1),","
     &    ,delta(3,1),",",delta(4,1),",",delta(5,1),",",delta(6,1),",",
     &    delta(7,1),","
       write(1,'(5x,a$)')"&  "
       write(1,'(7(f8.3,a))') delta(1,2),",",delta(2,2),",",
     &    delta(3,2),",",delta(4,2),",",delta(5,2),",",delta(6,2),",",
     &    delta(7,2),","
       write(1,'(5x,a$)')"&  "
       write(1,'(7(f8.3,a))') delta(1,3),",",delta(2,3),",",
     &    delta(3,3),",",delta(4,3),",",delta(5,3),",",delta(6,3),",",
     &    delta(7,3),","
       write(1,'(5x,a$)')"&  "
       write(1,'(7(f8.3,a))') delta(1,4),",",delta(2,4),",",
     &    delta(3,4),",",delta(4,4),",",delta(5,4),",",delta(6,4),",",
     &    delta(7,4),"/"
       write(1,'(6x,a)')"data beta"
```

```
  write(1,'(5x,a,7(f8.3,a))') "& /",beta(1,1),",",beta(2,1),",",
&   beta(3,1),",",beta(4,1),",",beta(5,1),",",beta(6,1),",",
&   beta(7,1),","
  write(1,'(5x,a$)')"&  "
  write(1,'(7(f8.3,a))') beta(1,2),",",beta(2,2),",",
&   beta(3,2),",",beta(4,2),",",beta(5,2),",",beta(6,2),",",
&   beta(7,2),","
  write(1,'(5x,a$)')"&  "
  write(1,'(7(f8.3,a))') beta(1,3),",",beta(2,3),",",
&   beta(3,3),",",beta(4,3),",",beta(5,3),",",beta(6,3),",",
&   beta(7,3),","
  write(1,'(5x,a$)')"&  "
  write(1,'(7(f8.3,a))') beta(1,4),",",beta(2,4),",",
&   beta(3,4),",",beta(4,4),",",beta(5,4),",",beta(6,4),",",
&   beta(7,4),"/"
  write(1,'(6x,a,f6.3,a)')"data eta   /",eta,"/"
  write(1,'(6x,a,f6.3,a)')"data kappa /",kappa,"/"
  write(1,'(6x,a)')"end"
 close(1)

 return

 end
```

Item A.7: Contents of file 'bdataYDP.f'

```
      block data
*     Bare soil        :  Desert Pavement, Yuma, AZ
*     Green vegetation:  0
*     Brown vegetation:  0
*     Forest canopy    :  0
      common /values/ b(7,9,4),c(7,9,4),delta(7,4),beta(7,4),eta,kappa
      real eta,kappa
      data b   /       0.9164613E-02,  0.1064413E-01,  0.1064413E-01,
     &  1.604921     ,  0.4686063E-02,  0.4686063E-02,
     & 0.9164613E-02,56*0.0,
     & 0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     & 0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     & 0.0000000E+00,56*0.0,
     & 0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     & 0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     & 0.0000000E+00,56*0.0,
     & 0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     & 0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     & 0.0000000E+00,56*0.0/
      data c   /       18.47000      ,   23.79000      ,   23.79000      ,
     &  107.9000     ,   36.31000     ,   36.31000      ,
     &  18.47000     ,56*0.0,
     & 0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     & 0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     & 0.0000000E+00,56*0.0,
     & 0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     & 0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     & 0.0000000E+00,56*0.0,
     & 0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     & 0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     & 0.0000000E+00,56*0.0/
      data delta    /-0.335, 0.610, 5.128,-13.22, 3.940,-4.569,-0.335,
     &                0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000,
     &                0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000,
     &                0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000/
      data beta     /-0.127, 1.470,-1.487,-7.348,-4.205, 4.139,-0.127,
     &                0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000,
     &                0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000,
     &                0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000/
      data eta   / 1.000/
      data kappa /-1.000/
      end
```

Item A.8: Contents of file 'bdataGTT.f'

```
      block data
*     Bare Soil        :  Coefficients from Yuma, AZ desert pavement modified
*                         to simulate test track at Grayling, MI
*     Green Vegetation:  0
*     Brown Vegetation:  0
*     Forest Canopy   :  0
      common /values/ b(7,9,4),c(7,9,4),delta(7,4),beta(7,4),eta,kappa
      real eta,kappa
      data b   /          0.1095171E-01,  0.1397042E-01,  0.1397042E-01,
     &  0.4931600E+00,  0.1740872E-01,  0.1740872E-01,
     &  0.1095171E-01,56*0.0,
     &  0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     &  0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     &  0.0000000E+00,56*0.0,
     &  0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     &  0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     &  0.0000000E+00,56*0.0,
     &  0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     &  0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     &  0.0000000E+00,56*0.0/
      data c   /           35.54000     ,    22.70000     ,    22.70000     ,
     &   26.45000     ,    30.83000     ,    30.83000     ,
     &   35.54000     ,56*0.0,
     &  0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     &  0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     &  0.0000000E+00,56*0.0,
     &  0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     &  0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     &  0.0000000E+00,56*0.0,
     &  0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     &  0.0000000E+00,  0.0000000E+00,  0.0000000E+00,
     &  0.0000000E+00,56*0.0/
      data delta   /-0.335, 0.610, 5.128,-13.22, 3.940,-4.569,-0.335,
     &               0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000,
     &               0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000,
     &               0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000/
      data beta   /-0.127, 1.470,-1.487,-7.348,-4.205, 4.139,-0.127,
     &               0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000,
     &               0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000,
     &               0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000/
      data eta   / 1.000/
      data kappa /-1.000/
      end
```

Item A.9: Contents of file 'texgen.c'

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <math.h>



typedef struct {
      float atime[25],
            temp[25],
            rad[25],
            temp1[25],
            rad1[25],
            temp2[25],
            rad2[25],
            avrad,
              minrad,
              maxrad,
            avrad1,
            avrad2;
      int num;
      int day;
} Diurnal;

float ar[26]={0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0};
int kflag[3]={0,0,0};
float xlv=0.0 ,xv=0.0,  resol;
Diurnal di;
double bandrad();
float bandrad0();
char str[90], *sptr;
int vegindicator=0;
float sunup,sundown;

 FILE *in, *texout;
char *clead(char str[])
{

    sptr=str;
    while(*sptr==' ' && *sptr!=0) sptr++;
    return sptr;
}
main(int ac, char *av[])
{
  float lemis,sabsr,sat;
  float thermc, thermd;
  float slope;

  if(ac<6) {
      puts("usage: texgen01 veg livveg resol inputfile outputfile");
      exit(1);
```

```
    }

    xv=atof(av[1]);
    xlv=atof(av[2]);
    resol=ar[15]=atof(av[3]);
    if((texout=fopen(av[5],"w"))==NULL)exit(1);

    if((in=fopen(av[4],"rt"))==NULL)exit(0);
    SetupStandardItems();

    GetRads();
    if(vegindicator==1) readveg();
    else if(vegindicator==0)readbare();
    else if(vegindicator==2)readcan();
}


readbare()
{
    register int k, i;
    float Tsdv;
    float p= 2.27E-07,  q = 1332.5;
    float T;
    float TB,TB2;


    fputs("Bare\n",texout);
    fputs("Time\tSdv\tCorrL\tTemp\tBrtTmp\tSdvBT\tRad\n"
         ,texout);
    fputs("----\t----\t-----\t----\t------\t-----\t----\n"
         ,texout);
    for(k=0;k<di.num;k++) {
         T=di.temp[k]+273.15;
       TB= q / (logf(1 + (1/ar[3]) * (expf(q/T) - 1))); /*JFM*/
       ar[0]=di.rad[k];
       ar[1]=0.0;
       ar[2]=ar[1];
       ar[16]=di.avrad;
       ar[17]=0.0;
       ar[18]=ar[16];
       ar[19]=di.atime[k];
       ar[22]=ar[21]=ar[20]=di.maxrad;
         ar[25]=ar[24]=ar[23]=di.minrad;
       sdaclor_(&xv,&xlv,kflag,ar);

       Tsdv=p*TB*TB*( exp(q/T) - 1.0 )*ar[0];
       fprintf(texout,"%4.2f\t%7.2f\t%7.2f\t%5.2f\t%5.2f\t%7.2f\t%5.2f\n"
            , di.atime[k],ar[0],ar[1] ,di.temp[k],TB-273.15
            ,Tsdv,di.rad[k]);

     }

}
readveg()
```

```
{
   register int k, i;
   float Tsdv;
   float p= 2.27E-07,  q = 1332.5, totrad;
   float T;
   float TB;


   SetupMVegItems();
   fputs("MVeg\n",texout);
   fputs("Time\tSdv\tCorrL\tTemp\tBrtTmp\tSdvBT\tRad\n"
        ,texout);
   fputs("----\t----\t-----\t----\t------\t-----\t----\n"
        ,texout);
   for(k=0;k<di.num;k++) {
        T=di.temp[k]+273.15;
      TB= q / (logf(1 + (1/ar[3]) * (expf(q/T) - 1))); /*JFM*/
      ar[0]=di.rad1[k];
      ar[1]=di.rad2[k];
      ar[2]=ar[1];
      ar[16]=di.avrad1;
      ar[17]=di.avrad2;
      ar[18]=ar[17];
      ar[19]=di.atime[k];
      ar[22]=ar[21]=ar[20]=di.maxrad;
      ar[25]=ar[24]=ar[23]=di.minrad;

      sdaclor_(&xv,&xlv,kflag,ar);


      Tsdv=p*TB*TB*( exp(q/T) - 1.0 )*ar[0];

      fprintf(texout,"%4.2f\t%7.2f\t%7.2f\t%5.2f\t%5.2f\t%7.2f\t%5.2f\n"
           , di.atime[k],ar[0],ar[1] ,di.temp[k],TB-273.15
           ,Tsdv,di.rad[k]);

      totrad=ar[9]*xv*di.rad1[k]+ar[3]*(1-xv)*di.rad2[k];

   }

}


readcan()
{
   register int k, i;
   float Tsdv;
   float p= 2.27E-07,  q = 1332.5, totrad;
   float T;
   float TB;


   SetupCanItems();
   fputs("Canopy\n",texout);
```

```
     fputs("Time\tSdv\tCorrL\tTemp\tBrtTmp\tSdvBT\tRad\n"
          ,texout);
     fputs("----\t----\t-----\t----\t------\t-----\t----\n"
          ,texout);
     for(k=0;k<di.num;k++)  {
          T=di.temp[k]+273.15;
        TB= q / (logf(1 + (1/ar[3]) * (expf(q/T) - 1))); /*JFM*/
        ar[0]=di.rad[k];
        ar[9]=resol;
        ar[10]=di.atime[k];
        ar[7]=0.5;
        ar[11]=di.avrad;
        ar[12]=di.maxrad;
        ar[13]=di.minrad;


        fsdaclor_(kflag,ar);

        Tsdv=p*T*T*( exp(q/T) - 1.0 )*ar[0];

        fprintf(texout,"%4.2f\t%7.2f\t%7.2f\t%5.2f\t%5.2f\t%7.2f\t%5.2f\n"
             , di.atime[k],ar[0],ar[1] ,di.temp[k],TB-273.15
             ,Tsdv,di.rad[k]);



     }
}


int GetRads()
{
   float atime,temp,rad,temp1,rad1,temp2,rad2;
   register i;

    rewind(in);
    di.avrad=di.avrad1=di.avrad2=0;
    di.maxrad=0.0;
    di.minrad=200.0;

    if(vegindicator) while(!feof(in)) {
      if(fgets(str,80,in)==NULL) break;
      if(!strncmp("-----REF",clead(str),8))
/* for vegetation */

      for(i=0;i<24;i++) {
          if(fgets(str, 80, in)==NULL)break;
          sscanf(str,"%f %*f %*f %*f %f %f %f",
            &atime, &temp, &temp1,&temp2);
          di.atime[i]=atime;

          di.temp[i]=temp;
/*
          di.rad[i]=bandrad(temp+273.15, 8.0, 12.0);
```

```
*/
        di.rad[i]=bandrad0(temp+273.15,ar[3]);

        if (di.maxrad < di.rad[i]) di.maxrad = di.rad[i];
        if (di.minrad > di.rad[i]) di.minrad = di.rad[i];

      di.avrad +=di.rad[i];

      di.temp1[i]=temp1;
/*
      di.rad1[i]=bandrad(temp1+273.15, 8.0, 12.0);
*/
        di.rad1[i]=bandrad0(temp1+273.15,ar[3]);
      di.avrad1 +=di.rad1[i];

      di.temp2[i]=temp2;
/*
      di.rad2[i]=bandrad(temp2+273.15, 8.0, 12.0);
*/
        di.rad2[i]=bandrad0(temp2+273.15,ar[3]);
      di.avrad2 +=di.rad2[i];


   }
  }


  if(!vegindicator)while(!feof(in)) {
    if(fgets(str,80,in)==NULL) break;
    if(!strncmp("DEG C",clead(str),5))
/* for vegetation */
    for(i=0;i<24;i++) {
        if(fgets(str, 80, in)==NULL)break;
        sscanf(str,"%f %f",&atime,&temp);
        di.atime[i]=atime;

        di.temp[i]=temp;
/*
        di.rad[i]=bandrad(temp+273.15, 8.0, 12.0);
*/
          di.rad[i]=bandrad0(temp+273.15,ar[3]);
          if (di.maxrad < di.rad[i]) di.maxrad = di.rad[i];
          if (di.minrad > di.rad[i]) di.minrad = di.rad[i];
        di.avrad +=di.rad[i];

        di.temp1[i]=0;
        di.rad1[i]=0;

        di.temp2[i]=0;
        di.rad2[i]=0;


    }
```

```
    }

    di.num=i;
    if(di.atime[i-1]==0.0)di.atime[i-1]+=24.0;
    if(di.num==0)return(0);
    di.avrad /=di.num;
    di.avrad1 /=di.num;
    di.avrad2 /=di.num;
    FindSunupDown();
    return(0);
}
int FindSunupDown()
{
    float atime[30], asolar;
    register int i=0, flag=0;

    rewind(in);
    while(!feof(in)) {
      if(fgets(str,80,in)==NULL) break;
      if(!strncmp("TIME  AIR", clead(str), 9))break;
    }
    if(fgets(str, 80, in)==NULL)return 0;

    while(!feof(in)) {
      if(fgets(str, 80, in)==NULL)break;
      sscanf(str, "%f %*f %*f %*f %*f %f", &atime[i], &asolar);
      if(!flag && asolar!=0.0) {
          sunup=atime[i]; /* sunu */
          flag=1;
      }
      else if(flag && asolar==0.0) {
            sundown=atime[i-1]; /* sundown */
            break;
      }
      i++;
      if(i>29)return 0;
    }

}


int SetupStandardItems()
{
   float heatcond,thermaldiff,emiss,absorp,satur;
   float slope;
   register i;

   rewind(in);
   while(!feof(in)) {
    if(fgets(str,80,in)==NULL) break;
    if(!strncmp("VEGETATION", clead(str), 10))
       vegindicator=1;
    if(!strncmp("CANOPY", clead(str), 6))
```

```
        vegindicator=2;

      if(!strncmp("EMISS",clead(str),5)) {
        fgets(str,80,in);
        sscanf(str,"%f %f %f",&emiss,&absorp,&satur);
      }

      if(!strncmp("NO.     C",clead(str),8)) {
        fgets(str,80,in);
        sscanf(str,"%*d %*f %*f %f %f",&thermaldiff,&heatcond);
      }

      if(!strncmp("SFC SLOPE", clead(str), 9))
      {
        fgets(str, 80, in);
        fgets(str, 80, in);
        sscanf(str, "%f", &slope);
      }
     }

     ar[3]=emiss;
     ar[4]=absorp;
     ar[5]=heatcond;
     ar[6]=thermaldiff;
     ar[7]=satur;
     ar[8]=slope;

     return(0);
}
int SetupMVegItems()
{
   float folcov,emiss,absorp;

   rewind(in);
   while(!feof(in)) {
    if(fgets(str,80,in)==NULL) break;
    if(!strncmp("COVERAGE",clead(str),8)) {
      fgets(str,80,in);
      fgets(str,80,in);
      sscanf(str,"%f %*f %f %f",&folcov, &emiss, &absorp);
      break;
    }
   }



    xv=folcov;
    ar[12]=ar[9]=emiss;
    ar[13]=ar[10]=absorp;
    return(0);
}
```

```
int SetupCanItems()
{

   float folcov,emiss,absorp;
   float lai, stoma;

   rewind(in);
   while(!feof(in)) {
    if(fgets(str,80,in)==NULL) break;
    if(!strncmp("COVERAGE",clead(str),8)) {
      fgets(str,80,in);
      fgets(str,80,in);
      sscanf(str,"%f %*f %f %f",&folcov, &emiss, &absorp);
      break;
    }
   }


    lai=7.0*folcov;  /* this is strictly made up */
    stoma=.333;        /* so is this */


    xv=folcov;
    ar[2]=ar[1]=emiss;
    ar[5]=absorp;
    ar[8]=stoma;
    ar[6]=lai;

    return(0);
}

float bandrad0(tmp,epsilon)
float tmp;
float epsilon;
{
        float rad;

        rad = 3305.8/( expf(1332.5/tmp) - 1.0 )*epsilon;

        return(rad);
}

/*
double bandrad(tmp,lam1,lam2)
double tmp,lam1,lam2;
{
      float band_frac;
      float next,v,sum1,sum2,m,mv;

      v=14388.0/(lam1*tmp);
      m=1.0;
      sum1=0;
      mv=m*v;
      next= exp(-mv)/pow(m,4.0)*(((mv+3)*mv+6)*mv+6);
```

```
        do {
              sum1+= next;
              m++;
              mv=m*v;
              next= exp(-mv)/pow(m,4.0)*(((mv+3)*mv+6)*mv+6);
        } while( m<=10);
        sum1=15.0/97.40909*sum1;

        v=14388.0/(lam2*tmp);
        m=1.0;
        sum2=0;
        mv=m*v;
        next= exp(-mv)/pow(m,4.0)*(((mv+3)*mv+6)*mv+6);
        do {
              sum2+= next;
              m++;
              mv=m*v;
              next= exp(-mv)/pow(m,4.0)*(((mv+3)*mv+6)*mv+6);
        } while( m<=10);
        sum2=15.0/97.40909*sum2;
        band_frac=((sum2-sum1)*5.67e-8*pow(tmp,4.0)) / 3.1415926;
        return(band_frac);
}
*/
```

Item A.10: Contents of file 'sdaclor.f'

```
**********************************************************************
      subroutine sdaclor(xv,xlv,kflag,a)
**********************************************************************
*     This subroutine is based on equations 26 and 27 on page 13 of   *
*     the report "Physics Based IR Terrain Radiance Texture Model"    *
*     by Richard A. Weiss and Bruce M. Sabol of the US Army           *
*     Waterways Experiment Station, Vicksburg, MS 39180 for           *
*     James A. Smith, Laboratory for Terrestrial Physics,             *
*     NASA Goddard Space Flight Center, Greenbelt, MD 20771           *
**********************************************************************
      real xv     ! fraction of terrain covered by vegetation
      real xlv    ! fraction of vegetation cover that is green
      real a(22) ! input/output vector
      integer kflag(3) !  Noon/afternoon flag
      real x(4)
**********************************************************************
*     on input, a( 1) - radiance of bare soil                         *
*               a( 2) - radiance of live vegetation                   *
*               a( 3) - radiance of dead vegetation                   *
*               a( 4) - longwave emissivity of soil                   *
*               a( 5) - shortwave absorptivity of soil                *
*               a( 6) - heat conductivity of soil                     *
*               a( 7) - thermal diffusivity of soil                   *
*               a( 8) - soil moisture                                 *
*               a( 9) - average terrain slope for soil                *
*               a(10) - longwave emissivity of green vegetation       *
*               a(11) - shortwave absorptivity of green vegetation    *
*               a(12) - average terrain slope for green vegetation    *
*               a(13) - longwave emissivity of brown vegetation       *
*               a(14) - shortwave absorptivity of brown vegetation    *
*               a(15) - average terrain slope for brown vegetation    *
*               a(16) - resolution                                    *
*               a(17) - diurnal average radiance of bare soil         *
*               a(18) - diurnal average radiance of live vegetation   *
*               a(19) - diurnal average radiance of dead vegetation   *
*               a(20) - time of day                                   *
*               a(21) - diurnal maximum radiance of bare soil         *
*               a(22) - diurnal maximum radiance of live vegetation   *
*               a(23) - diurnal maximum radiance of dead vegetation   *
*               a(24) - diurnal minimum radiance of bare soil         *
*               a(25) - diurnal minimum radiance of live vegetation   *
*               a(26) - diurnal minimum radiance of dead vegetation   *
*    on return, a( 1) - standard deviation of radiance                *
*               a( 2) - correlation length of radiance                *
**********************************************************************
      integer band(3)    ! band selector
      real u(3),e(3)
      real msd(3)  ! standard deviation multipliers
      ! msd(1)       for soil
      ! msd(2)       for green vegetation
      ! msd(3)       for brown vegetation
```

```
      real mcl(3)  ! correlation length multipliers
      ! mcl(1)       for soil
      ! mcl(2)       for green vegetation
      ! mcl(3)       for brown vegetation
      real sdvs    ! standard deviation of radiance for soil/vegetation
      real clvs    ! correlation length/mixed soil & vegetation
      real varv    ! variance in radiance for vegetation
*******************************************************************
*     The values of b,c,delta,beta,eta and kappa are initialized in   *
*     a block data subroutine under the block "values".  In this way  *
*     different data sets can be accomodated by changing out the      *
*     block data module.                                              *
*******************************************************************
      real b(7,9,4),c(7,9,4)     ! vector constants
      ! ?(band,*,1)                 soil vector constants
      ! ?(band,*,2)                 green vegetation vector constants
      ! ?(band,*,3)                 brown vegetation vector constants
      ! ?(band,*,4)                 forest canopy vector constants
      real delta(7,4) ! standard deviation exponents
      ! delta(band,1)    for soil
      ! delta(band,2)    for green vegetation
      ! delta(band,3)    for brown vegetation
      ! delta(band,4)    for forest canopy
      real beta(7,4)  ! correlation length exponents
      ! beta(band,1)     for soil
      ! beta(band,2)     for green vegetation
      ! beta(band,3)     for brown vegetation
      ! beta(band,4)     for forest canopy
      real eta,kappa  ! resolution exponents
      common /values/ b(7,9,4),c(7,9,4),delta(7,4),beta(7,4),eta,kappa

*******************************************************************
*     Normalize the radiance values:                                  *
*******************************************************************
      do i=1,3
         if ( a(i+16) .eq. 0.0 ) then
            a(i) = 0.0
         else
            a(i) = a(i)/a(i+16)
         end if
      end do

*******************************************************************
*     Determine which band to retrieve  values from:                  *
*******************************************************************
      do i=1,3
         x(1) = a(i)        ! radiance
         x(2) = a(i+16)     ! diurnal average radiance
         x(3) = a(i+20)     ! diurnal maximum radiance
         x(4) = a(i+23)     ! diurnal minimum radiance
         call adj(x,b,delta,i)
         call adj(x,c,beta,i)
         call get_band(i,kflag,x,band)
      end do
```

```
************************************************************************
*     Compute standard deviation and correlation length multipliers    *
*     for bare soil.                                                   *
************************************************************************
      msd(1)  = 0.0
      mcl(1)  = 0.0
      do i = 4,9
         msd(1) = msd(1) + b(band(1),i-2,1)*a(i)
         mcl(1) = mcl(1) + c(band(1),i-2,1)*a(i)
      end do
      msd(1) = msd(1) + b(band(1),1,1)
      mcl(1) = mcl(1) + c(band(1),1,1)

************************************************************************
*     Compute standard deviation and correlation length multipliers    *
*     for green vegetation.                                            *
************************************************************************
      msd(2) = 0.0
      mcl(2) = 0.0
      do i = 10,12
         msd(2) = msd(2) + b(band(2),i-8,2)*a(i)
         mcl(2) = mcl(2) + c(band(2),i-8,2)*a(i)
      end do
      msd(2) = msd(2) + b(band(2),1,2)
      mcl(2) = mcl(2) + c(band(2),1,2)

************************************************************************
*     Compute standard deviation and correlation length multipliers    *
*     for brown vegetation.                                            *
************************************************************************
      msd(3) = 0.0
      mcl(3) = 0.0
      do i = 13,15
         msd(3) = msd(3) + b(band(3),i-11,3)*a(i)
         mcl(3) = mcl(3) + c(band(3),i-11,3)*a(i)
      end do
      msd(3) = msd(3) + b(band(3),1,3)
      mcl(3) = mcl(3) + c(band(3),1,3)

************************************************************************
*     Equation 26, page 13 of report cited above:                      *
************************************************************************
*     on input, a( 1) = radiance of bare soil                          *
*               a( 2) = radiance of live vegetation                    *
*               a( 3) = radiance of dead vegetation                    *
*               a(16) = resolution                                     *
************************************************************************
      do i=1,3
         if ( a(i) .le. 0.0 ) then
            u(i) = 0.0
         else
            u(i) = a(i)**delta(band(i),i)
         end if
      end do
```

```
      varv =  (1.0 - xlv)*(msd(3)*u(3))**2 + xlv*(msd(2)*u(2))**2
      sdvs = a(16)**eta*sqrt((1.0-xv)*(msd(1)*u(1))**2+xv*varv)

*********************************************************************
*     Equation 27, page 13 of report cited above:                  *
*********************************************************************

      do i=1,3
         if ( a(i) .le. 0.0 ) then
            v = 0.0
         else
            v = a(16)**kappa*mcl(i)*a(i)**beta(band(i),i)
         end if
         if ( v .eq. 0.0 ) then
            e(i) = 0.0
         else
            e(i) = exp(-1.0/v)
         end if
      end do
      r = (1.0-xv)*e(1) + xv*( (1.0-xlv)*e(3) + xlv*e(2) )
      clvs = -1.0/alog(r)

      a(1) = sdvs
      a(2) = clvs

      return
      end ! sdaclor

**********************************************************************
      subroutine get_band(i,kflag,xx,band)

      real xx(4)
      integer band(3)
      integer kflag(3)

      data s /0.5/
      data t /0.84/

      x = xx(1)
      rn = xx(4)/xx(2)
      rx = xx(3)/xx(2)
      ra = (1.0 - s)*rn + s
      rb = 1.0 - t + t*rx

      if ( kflag(i) .eq. 0 .and. x .lt. ra ) then
         band(i) = 1
      else if ( kflag(i) .eq. 0 .and. ra .le. x .and. x .lt. 1.0) then
         band(i) = 2
      else if ( kflag(i) .eq. 0 .and. x .ge. 1.0 .and. x .lt. rb ) then
         band(i) = 3
      else if ( kflag(i) .eq. 0 .and. x .ge. rb .and. x .le. rx ) then
         band(i) = 4
         if ( rx - x .le. 0.0001 ) then
            kflag(i) = 1
```

```
         end if
      else if ( kflag(i) .eq. 1 .and. 1.0 .le. x ) then
         band(i) = 5
      else if ( kflag(i) .eq. 1 .and. ra .le. x .and. x .lt. 1.0 ) then
         band(i) = 6
      else
         band(i) = 7
      end if

      return
      end
************************************************************************
      subroutine adj(x,a,b,i)
      real x(4),a(7,9,4),b(7,9,4)
      data s /0.50/
      data t /0.84/

      rmax = x(3)/x(2)
      rmin = x(4)/x(2)
      ra = (1.0 - s)*rmin + s
      rb = 1.0 - t + t*rmax
      a1 = a(1,1,i)
      a3 = a(3,1,i)
      a5 = a(5,1,i)
      b1 = b(1,1,i)
      b3 = b(3,1,i)
      b5 = b(5,1,i)

      a(2,1,i) = a3
      a(6,1,i) = a5
      b(2,1,i) = b1 + (alog(a1)-alog(a3))/alog(ra)
      b(4,1,i) = alog( a3*rb**b3/(a5*rmax**b5) )/alog(rb/rmax)
      b(6,1,i) = b1 + (alog(a1) - alog(a5))/alog(ra)
      a(4,1,i) = a5*rmax**(b5 - b(4,1,i))

      return
      end
```

Item A.11: Contents of file 'fsdaclor.f'

```
***********************************************************************
      subroutine fsdaclor(kflag,a)
***********************************************************************
*     This subroutine is based on equations 50 and 51 on page 18 of   *
*     the report "Physics Based IR Terrain Radiance Texture Model"    *
*     by Richard A. Weiss and Bruce M. Sabol of the US Army           *
*     Waterways Experiment Station, Vicksburg, MS 39180 for           *
*     James A. Smith, Laboratory for Terrestrial Physics,             *
*     NASA Goddard Space Flight Center, Greenbelt, MD 20771           *
***********************************************************************
      real a(14)    ! input/output vector
***********************************************************************
*     on input, a( 1) = computed radiance of forest canopy            *
*               a( 2) = longwave emissivity of leaves                 *
*               a( 3) = longwave absorptivity of leaves               *
*               a( 4) = longwave emissivity of soil                   *
*               a( 5) = longwave absorptivity of soil                 *
*               a( 6) = shortwave absorptivity of leaves              *
*               a( 7) = leaf area index                               *
*               a( 8) = leaf slope distribution                       *
*               a( 9) = stomatal resistance to water vapor diffusion  *
*               a(10) = resolution                                    *
*               a(11) = time of day                                   *
*               a(12) = average diurnal radiance of canopy            *
*               a(13) = maximum diurnal radiance of canopy            *
*               a(14) = minimum diurnal radiance of canopy            *
*    on return, a( 1) = standard deviation of radiance                *
*               a( 2) = correlation length of radiance                *
***********************************************************************
      real x(4)
      real b(7,9,4),c(7,9,4)     ! vector constants
      ! ?(band,*,1)                soil vector constants
      ! ?(band,*,2)                green vegetation vector constants
      ! ?(band,*,3)                brown vegetation vector constants
      ! ?(band,*,4)                forest canopy vector constants
      real delta(7,4) ! standard deviation exponents
      ! delta(band,1)    for soil
      ! delta(band,2)    for green vegetation
      ! delta(band,3)    for brown vegetation
      ! delta(band,4)    for forest canopy
      real beta(7,4)  ! correlation length exponents
      ! beta(band,1)     for soil
      ! beta(band,2)     for green vegetation
      ! beta(band,3)     for brown vegetation
      ! beta(band,4)     for forest canopy
      real eta,kappa  ! resolution exponents
      common /values/ b(7,9,4),c(7,9,4),delta(7,4),beta(7,4),eta,kappa
***********************************************************************
      real msd      ! standard deviation multiplier
      real mcl      ! correlation length multiplier
      real sd       ! standard deviation of radiance
```

```
      real cl      ! correlation length of radiance
      integer band ! time of day band

************************************************************************
*     Normalize radiance
************************************************************************
      if ( a(12) .le. 0.0 ) then
         a(1) = 0.0
      else
         a(1) = a(1)/a(12)
      end if

      x(1) = a(1)
      x(2) = a(12)
      x(3) = a(13)
      x(4) = a(14)

      call adj(x,b,delta,4)
      call adj(x,c,beta,4)
      call get_band(1,kflag,x,band)

************************************************************************
*     Compute standard deviation and correlation length multipliers    *
************************************************************************

      msd  = 0.0
      mcl  = 0.0
      do i = 2,9
         msd = msd + b(band,i-1,4)*a(i)
         mcl = mcl + c(band,i-1,4)*a(i)
      end do
      msd = msd + b(band,1,4)
      mcl = mcl + c(band,1,4)

************************************************************************
*     Equation 54, 55, pages 19,20 of report cited above:              *
************************************************************************
*     on input, a( 1) = radiance of bare soil                          *
*               a(10) = resolution                                     *
************************************************************************

      if ( a(1) .le. 0.0 ) then
         sd = 0.0
         cl = 0.0
      else
         sd = a(10)**eta*a(1)**delta(band,4)*msd
         cl = a(10)**kappa*a(1)**beta(band,4)*mcl
      end if

      a(1) = sd
      a(2) = cl

      return
      end ! fsdaclor
```

Appendix B
Data Files

Item B.1: Contents of file 'ss040893.dat' (Yuma, AZ)

Resolution Range: 0.01853 0.01668

IMAGE DATETIME	FEATURE DESCRIPTION	IMAGE MEAN W/(M^2*SR)	STD. DEV. W/(M^2*SR)	CORRELATON LENGTH (METERS)
08APR93:00:34	GRASS-BARESOIL	28.575	0.5002	0.3100
08APR93:01:04	GRASS-BARESOIL	29.182	0.4761	0.3000
08APR93:01:13	GRASS-BARESOIL	29.255	0.4686	0.3600
08APR93:02:39	GRASS-BARESOIL	28.313	0.5103	0.3000
08APR93:03:14	GRASS-BARESOIL	27.703	0.4443	0.2600
08APR93:03:20	GRASS-BARESOIL	27.740	0.4452	0.2200
08APR93:04:16	GRASS-BARESOIL	26.441	0.3373	0.1800
08APR93:04:40	GRASS-BARESOIL	26.827	0.3571	0.2100
08APR93:05:05	GRASS-BARESOIL	26.827	0.4202	0.2800
08APR93:05:25	GRASS-BARESOIL	27.971	0.5620	0.2900
08APR93:06:13	GRASS-BARESOIL	27.896	0.5018	0.2800
08APR93:06:32	GRASS-BARESOIL	28.009	0.4683	0.2800
08APR93:07:12	GRASS-BARESOIL	31.092	0.6329	0.3100
08APR93:07:28	GRASS-BARESOIL	32.943	0.5968	0.3400
08APR93:08:07	GRASS-BARESOIL	35.172	0.4137	0.4500
08APR93:08:28	GRASS-BARESOIL	36.723	0.3555	0.4200
08APR93:09:16	GRASS-BARESOIL	39.793	0.4108	0.3600
08APR93:09:32	GRASS-BARESOIL	40.677	0.5411	0.4000
08APR93:10:10	GRASS-BARESOIL	42.947	0.7266	0.3000
08APR93:10:29	GRASS-BARESOIL	43.820	0.8384	0.2700
08APR93:11:06	GRASS-BARESOIL	45.024	0.8719	0.2900
08APR93:11:31	GRASS-BARESOIL	45.951	1.0743	0.2400
08APR93:12:08	GRASS-BARESOIL	47.594	1.1358	0.1600
08APR93:12:32	GRASS-BARESOIL	47.492	1.3077	0.2000
08APR93:13:04	GRASS-BARESOIL	48.305	1.3966	0.2500
08APR93:13:19	GRASS-BARESOIL	48.170	1.2517	0.1600
08APR93:14:14	GRASS-BARESOIL	50.432	1.3791	0.2200
08APR93:14:27	GRASS-BARESOIL	49.796	1.4170	0.1400
08APR93:15:09	GRASS-BARESOIL	49.927	1.1929	0.1500
08APR93:15:34	GRASS-BARESOIL	48.543	1.0595	0.1100
08APR93:16:03	GRASS-BARESOIL	48.067	1.0793	0.1500
08APR93:16:18	GRASS-BARESOIL	47.320	0.8920	0.1500
08APR93:18:09	GRASS-BARESOIL	41.904	0.2828	0.2000
08APR93:18:28	GRASS-BARESOIL	40.572	0.3489	0.2900
08APR93:19:07	GRASS-BARESOIL	37.691	0.3938	0.6100
08APR93:19:32	GRASS-BARESOIL	36.041	0.2935	0.3300
08APR93:20:03	GRASS-BARESOIL	34.699	0.2445	0.2900
08APR93:20:29	GRASS-BARESOIL	33.528	0.2622	0.2400
08APR93:21:05	GRASS-BARESOIL	32.870	0.2572	0.3400
08APR93:21:34	GRASS-BARESOIL	32.020	0.2899	0.3800
08APR93:22:06	GRASS-BARESOIL	31.536	0.3586	0.2500
08APR93:22:36	GRASS-BARESOIL	31.203	0.4163	0.2700
08APR93:23:10	GRASS-BARESOIL	31.203	0.4482	0.2200
08APR93:23:22	GRASS-BARESOIL	30.832	0.3793	0.2200

Item B.2: Contents of file 'ss042693.dat' (Yuma, AZ)

Resolution Range: 0.02363 0.02041

IMAGE DATETIME	FEATURE DESCRIPTION	IMAGE MEAN W/(M^2*SR)	STD. DEV. W/(M^2*SR)	CORRELATON LENGTH (METERS)
26APR93:00:06	SLOPE-DESPAV	31.908	0.3989	0.4400
26APR93:00:20	SLOPE-DESPAV	32.168	0.4600	0.4700
26APR93:01:11	SLOPE-DESPAV	32.503	0.3898	0.4000
26APR93:01:36	SLOPE-DESPAV	32.647	0.5580	0.3900
26APR93:02:03	SLOPE-DESPAV	32.539	0.5141	0.3800
26APR93:02:23	SLOPE-DESPAV	32.575	0.6027	0.3900
26APR93:03:04	SLOPE-DESPAV	31.760	0.4074	0.4000
26APR93:03:36	SLOPE-DESPAV	31.057	0.4023	0.4500
26APR93:04:02	SLOPE-DESPAV	31.057	0.4569	0.4800
26APR93:04:33	SLOPE-DESPAV	30.383	0.3762	0.4600
26APR93:05:03	SLOPE-DESPAV	30.235	0.4456	0.4600
26APR93:05:13	SLOPE-DESPAV	30.195	0.4531	0.4500
26APR93:06:03	SLOPE-DESPAV	30.195	0.4639	0.3800
26APR93:06:14	SLOPE-DESPAV	30.757	0.5331	0.3400
26APR93:07:02	SLOPE-DESPAV	34.774	0.6056	0.3000
26APR93:07:33	SLOPE-DESPAV	37.837	0.4779	0.3000
26APR93:08:08	SLOPE-DESPAV	41.625	0.4227	0.3600
26APR93:08:21	SLOPE-DESPAV	43.991	0.5402	0.4800
26APR93:09:01	SLOPE-DESPAV	47.085	0.8603	0.4800
26APR93:09:48	SLOPE-DESPAV	49.626	1.3169	0.3700
26APR93:10:01	SLOPE-DESPAV	51.033	1.4664	0.4300
26APR93:10:27	SLOPE-DESPAV	53.664	1.6298	0.4000
26APR93:11:05	SLOPE-DESPAV	54.951	1.7390	0.4300
26APR93:11:33	SLOPE-DESPAV	55.774	1.8408	0.4200
26APR93:12:01	SLOPE-DESPAV	55.774	1.6861	0.3100
26APR93:12:18	SLOPE-DESPAV	56.491	1.5996	0.3600
26APR93:13:02	SLOPE-DESPAV	57.509	1.1794	0.2500
26APR93:13:26	SLOPE-DESPAV	57.178	1.0663	0.2800
26APR93:14:08	SLOPE-DESPAV	56.981	1.0279	0.2800
26APR93:14:43	SLOPE-DESPAV	56.596	0.7786	0.2900
26APR93:15:08	SLOPE-DESPAV	56.198	0.6486	0.2000
26APR93:15:19	SLOPE-DESPAV	56.393	0.6901	0.1900
26APR93:16:03	SLOPE-DESPAV	54.689	0.4507	0.2800
26APR93:16:35	SLOPE-DESPAV	52.340	0.4064	0.2400
26APR93:17:11	SLOPE-DESPAV	51.971	0.3904	0.5400
26APR93:17:22	SLOPE-DESPAV	50.366	0.3738	0.5100
26APR93:18:04	SLOPE-DESPAV	47.047	0.2939	0.7500
26APR93:18:19	SLOPE-DESPAV	46.089	0.2834	0.5800
26APR93:19:08	SLOPE-DESPAV	42.220	0.3900	0.5600
26APR93:19:28	SLOPE-DESPAV	40.642	0.3151	0.4700
26APR93:20:03	SLOPE-DESPAV	38.942	0.3592	0.5000
26APR93:20:32	SLOPE-DESPAV	37.911	0.2940	0.5000
26APR93:21:03	SLOPE-DESPAV	37.194	0.3398	0.5400
26APR93:21:32	SLOPE-DESPAV	36.690	0.3018	0.5400
26APR93:22:05	SLOPE-DESPAV	36.579	0.3324	0.5200
26APR93:22:33	SLOPE-DESPAV	36.403	0.5190	0.3900

26APR93:23:03	SLOPE-DESPAV	35.643	0.2804	0.3900
26APR93:23:34	SLOPE-DESPAV	35.318	0.4922	0.3700

Item B.3: Contents of file 'ss040893.prm'

```
eta   -   1.00
kappa -  -1.00
08APR93      SLOPE-DESPAV
Bandsize 1,3,4,5:  16    6    5    7
Minimum Radiance / Average Radiance - 0.705
Maximum Radiance / Average Radiance - 1.404
band          b           delta       c        beta
----    -------------     -----    -------     -----
  1     0.8540429E-02     -0.618     27.10     1.081
  2     0.1022623E-01      0.510     25.87     0.790
  3     0.1022623E-01      4.963     25.87    -2.255
  4      1.924964        -13.484     39.40    -4.011
  5     0.7756619E-02      1.430     23.83    -2.831
  6     0.7756619E-02     -1.221     23.83     0.275
  7     0.8540429E-02     -0.618     27.10     1.081
```

Item B.4: Contents of file 'ss042693.prm'

```
eta   =   1.00
kappa =  -1.00
26APR93       SLOPE-DESPAV
Bandsize 1,3,4,5:  17    6    4   11
Minimum Radiance / Average Radiance = 0.709
Maximum Radiance / Average Radiance = 1.351
band          b            delta        c        beta
----    -------------      -----    -------     -----
  1     0.9793684E-02     -0.069     12.88     -1.264
  2     0.1107910E-01      0.716     21.88      2.111
  3     0.1107910E-01      5.294     21.88     -0.718
  4      1.278622        -12.884    380.12    -11.520
  5     0.3400406E-02      5.538     47.47     -5.080
  6     0.3400406E-02     -6.803     47.47      7.042
  7     0.9793684E-02     -0.069     12.88     -1.264
```

Item B.5: Contents of file 'ss.all'

```
eta   -   1.00
kappa -  -1.00
08APR93       SLOPE-DESPAV
Bandsize 1,3,4,5:  16     6     5     7
Minimum Radiance / Average Radiance - 0.705
Maximum Radiance / Average Radiance - 1.404
band          b           delta       c         beta
----    -------------     -----    -------     -----
  1     0.8540429E-02    -0.618     27.10      1.081
  2     0.1022623E-01     0.510     25.87      0.790
  3     0.1022623E-01     4.963     25.87     -2.255
  4      1.924964       -13.484     39.40     -4.011
  5     0.7756619E-02     1.430     23.83     -2.831
  6     0.7756619E-02    -1.221     23.83      0.275
  7     0.8540429E-02    -0.618     27.10      1.081
26APR93       SLOPE-DESPAV
Bandsize 1,3,4,5:  17     6     4    11
Minimum Radiance / Average Radiance - 0.709
Maximum Radiance / Average Radiance - 1.351
band          b           delta       c         beta
----    -------------     -----    -------     -----
  1     0.9793684E-02    -0.069     12.88     -1.264
  2     0.1107910E-01     0.716     21.88      2.111
  3     0.1107910E-01     5.294     21.88     -0.718
  4      1.278622       -12.884    380.12    -11.520
  5     0.3400406E-02     5.538     47.47     -5.080
  6     0.3400406E-02    -6.803     47.47      7.042
  7     0.9793684E-02    -0.069     12.88     -1.264
```

Item B.6: Contents of file 'ss.avg'

```
eta   =   1.00
kappa =  -1.00
AVERAGES:       SLOPE-DESPAV
band        b            delta       c       beta
----  -------------      -----    -------    -----
  1   0.9164613E-02     -0.335     18.47    -0.127
  2   0.1064413E-01      0.610     23.79     1.470
  3   0.1064413E-01      5.128     23.79    -1.487
  4    1.604921        -13.217    107.90    -7.348
  5   0.4686063E-02      3.940     36.31    -4.205
  6   0.4686063E-02     -4.569     36.31     4.139
  7   0.9164613E-02     -0.335     18.47    -0.127
```

Item B.7: Contents of file 'model.db' (same as modelYDP.db)

```
eta   =   1.00
kappa =  -1.00
BARE SOIL
band        b             delta       c       beta
----   ------------       -----    -------    -----
  1    0.9164613E-02     -0.335     18.47    -0.127
  2    0.1064413E-01      0.610     23.79     1.470
  3    0.1064413E-01      5.128     23.79    -1.487
  4     1.604921        -13.217    107.90    -7.348
  5    0.4686063E-02      3.940     36.31    -4.205
  6    0.4686063E-02     -4.569     36.31     4.139
  7    0.9164613E-02     -0.335     18.47    -0.127
GREEN VEGETATION
band        b             delta       c       beta
----   ------------       -----    -------    -----
  1    0.0000000E+00      0.000      0.00     0.000
  2    0.0000000E+00      0.000      0.00     0.000
  3    0.0000000E+00      0.000      0.00     0.000
  4    0.0000000E+00      0.000      0.00     0.000
  5    0.0000000E+00      0.000      0.00     0.000
  6    0.0000000E+00      0.000      0.00     0.000
  7    0.0000000E+00      0.000      0.00     0.000
BROWN VEGETATION
band        b             delta       c       beta
----   ------------       -----    -------    -----
  1    0.0000000E+00      0.000      0.00     0.000
  2    0.0000000E+00      0.000      0.00     0.000
  3    0.0000000E+00      0.000      0.00     0.000
  4    0.0000000E+00      0.000      0.00     0.000
  5    0.0000000E+00      0.000      0.00     0.000
  6    0.0000000E+00      0.000      0.00     0.000
  7    0.0000000E+00      0.000      0.00     0.000
FOREST CANOPY
band        b             delta       c       beta
----   ------------       -----    -------    -----
  1    0.0000000E+00      0.000      0.00     0.000
  2    0.0000000E+00      0.000      0.00     0.000
  3    0.0000000E+00      0.000      0.00     0.000
  4    0.0000000E+00      0.000      0.00     0.000
  5    0.0000000E+00      0.000      0.00     0.000
  6    0.0000000E+00      0.000      0.00     0.000
  7    0.0000000E+00      0.000      0.00     0.000
```

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13. ABSTRACT *(Maximum 200 words)*

This report develops a physics-based semiempirical model for predicting the texture of an infrared (IR) image of terrain areas including soil, grass, and forest canopies. The model is based on an empirical determination of the relationship between the standard deviation and correlation length of the terrain radiance variations in an IR image and the average value of the radiance in the image. The average value of the terrain radiance is then theoretically predicted by the WESTHERM terrain radiance prediction model in terms of local terrain and weather conditions and in terms of the time of day. In this way, the diurnal variation of the standard deviation and correlation length of the radiance or brightness temperature can be predicted for specified terrain and weather conditions.

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